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ABSTRACT

Intended to aid teachers of high ability elementary students in understanding the key components and generalizations that are critical to specific science concepts, this document contains eight papers addressing broad concepts common to many branches of science and teaching principles. A paper on the nature of the scientific process precedes six concept papers which address ideas of: (1) scale; (2) models; (3) change; (4) systems; (5) evolution; and (6) reductionism (structure, function, and pattern). Each of the papers defines the concept in question; gives examples of its relevance to a number of areas of inquiry, both scientific and nonscientific; gives a rationale for teaching the concept; and lists suggestions for teaching the concept to high ability learners at different grade levels. A final paper offers general suggestions that apply to the teaching of essentially all the concepts. This chapter considers appropriate use of laboratory activities in science programs for the gifted, problem-based learning, incorporating experiments and experimental design into a scientific problem-based learning experience, new science, scientists as classroom resources, and use of notebooks. References and additional readings for each concept are provided in a 38-item bibliography. (DB)

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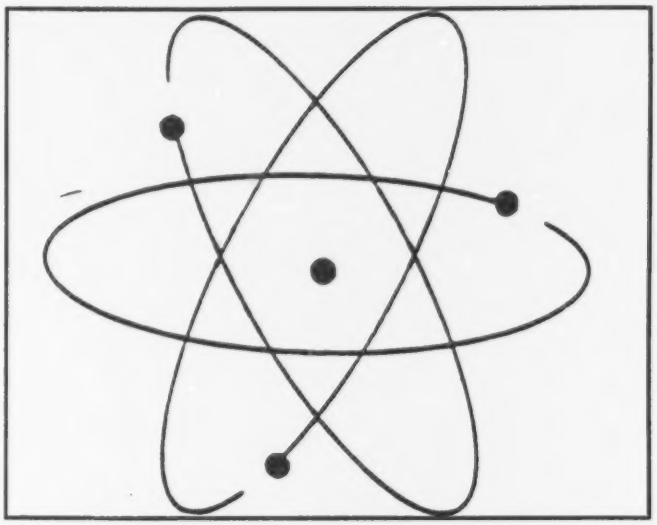
GUIDE TO SCIENCE CONCEPTS



Developing Science Curriculum for High Ability Learners K-8

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College of William and Mary
School of Education
Center for Gifted Education
Williamsburg, Virginia

1992

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- Consumer's Guide to Science Curriculum
- Guide to Science Concepts
- Scope and Sequence of K-8 Science Curriculum for High Ability Learners
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- Notes from a Scientist: Suggested Resources and Activities for Gifted Children

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College of William and Mary
School of Education
Center for Gifted Education
Williamsburg, Virginia

1992

GUIDE TO SCIENCE CONCEPTS

by

Beverly Sher

The College of William and Mary
School of Education
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Williamsburg, Virginia

1992

A Guide to Key Science Concepts

This document contains a series of concept papers that describe a number of broad, overarching, scientifically grounded concepts common to many branches of science. They were chosen with reference to the concepts selected by Rutherford and Ahlgren in Science for All Americans, those selected by the writers of the California Framework, and those selected by Horace F. Judson for his book Search for Solutions. Additional criteria applied to selecting the concepts in this project were: 1) ease of applicability to all science areas, 2) numerous valid connections to non-science domains of inquiry, and 3) highly workable to demonstrate content manifestations at the unit level of analysis.

Of all the concepts referred to in other works, six were chosen for explication: scale, models, change, systems, evolution, and reductionism. In addition, during the course of the project, a general description of the scientific process that would be useful for teachers to follow was developed. A description of useful ways to incorporate laboratory work for high ability learners was also developed and incorporated into this guide. Finally, an applications paper containing implementation suggestions common to work with any of the concepts has also been included.

Organization of Concept Papers

Each of the concept papers defines the concept in question; gives examples of its relevance to a number of areas of inquiry, both scientific and nonscientific; gives a rationale for teaching the concept; and lists suggestions for teaching the concept to high ability learners at different grade levels. References and additional readings for each concept may be found in the bibliography at the end of this document.

Purpose and Use of the Guide

T1he purpose of this guide is to aid teachers in understanding the key components and generalizations that are critical to specific science concepts as well as to see ways these concepts can be applied to high ability students' learning science in the classroom. Moreover, by providing a rich bibliography of further readings on each concept, teachers are encouraged to engage in the first step of the scientific process: learning as much as possible about what they are expected to teach.

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The Nature of the Scientific Process

What is science? Science is a process, a mode of inquiry about the world that surrounds us. Although different scientific disciplines are concerned with different facets of the natural world, they share some common approaches and characteristics. Scientists will deny that there is any special "scientific method", but in fact there are many similarities in the ways that scientists from different fields approach problems and in the standards that they set for scientific work. This concept paper will first explore the research process and then discuss the standards that distinguish "good" science from bad science and pseudoscience.

The Research Process

The research process is very similar across all scientific disciplines. This process contains elements of the "scientific method", although it is more complicated and less clear-cut than the standard litany of steps would suggest. The usual description of the scientific method consists of the following steps:

1. Generate a hypothesis.
2. Test the hypothesis experimentally.
3. Based on an analysis of the results of the experiment, reach a logical conclusion.

A more accurate description of the scientific research process includes the following steps:

1. Learn a great deal about your field.
2. Think of a good (interesting, important, and tractable) problem.
3. Decide which experiments/ observations/ calculations would contribute to a solution of the problem.
4. Perform the experiments/ observations/ calculations.
5. Decide whether the results really do contribute to a better understanding of the problem. If they don't, return to either step 2 (if you're very discouraged) or step 3. If they do, go to step 6.
6. Communicate your results to as many people as possible. If they're patentable, tell your lawyer before you tell anyone else, and write a patent application or two. Publish them in a scientific journal (as if they're really neat, in *The NewYork Times*); go to conferences and talk about them; tell all of your friends.

For the purposes of teaching science, the most important of the steps outlined above are probably steps 1-3 and step 6. These will now be discussed in detail.

Steps 1-3 should really be discussed together, as they are the most intellectually challenging part of the scientific process. The first step seems very obvious, yet is very important. The cutting edge of research is a long way from the level of the novice in most fields of science. In order to know approximately where the cutting edge of their discipline lies and to be able to adequately comprehend the latest research papers, most people must have at least an undergraduate degree in their discipline and some additional postgraduate courses. The body of available information is very large in essentially every area of science; in addition, some specialties (such as high energy physics) also require a great deal of math, some of which is taught at the graduate level. Without an understanding of the math

necessary for the discipline and a knowledge of at least the general shape of the field, the identification of a good problem is very difficult and its efficient solution is unlikely. In fact, the graduate education process is really an apprenticeship in finding and solving scientific problems; a Ph.D. degree is the union card that promises that a person should be competent to do original science. The acquisition of scientific knowledge must not stop after graduate courses end, either. Scientists spend a large amount of time sitting in seminars in which other people discuss their latest work, reading journals, and discussing the latest scientific gossip with their colleagues. One of the most exciting things about being a scientist is that the field changes every day, so there's always something new to think about.

The next step in the process is the identification of a good problem. A good scientific problem has a number of characteristics. First, the problem should be interesting to the scientific community and have some inherent importance. These two characteristics will be obvious to the person who thinks of the problem (providing, of course, that he has fulfilled step 1 adequately) and to his colleagues; they might not be obvious to a novice or the lay public. Second (and here begins step 3), the problem must be amenable to solution. If the problem is experimentally untestable or if the experiments required to solve it are technically almost impossible, incredibly expensive, or require several lifetimes to complete, then the problem should be shelved until new approaches become available.

After the problem has been identified and an experimental approach to its resolution has been outlined, the experiments/ observations/calculations can be performed and the results recorded. The results are analyzed and the scientist determines whether they are a significant contribution to the understanding of the original scientific problem. At this stage, the original statement of the problem may be refined and more work may be performed if necessary. Once the scientist is satisfied that her work is ready for sharing (see step 5), the results are communicated to the rest of the scientific community.

Because of the reward system in science, communication usually occurs as rapidly as possible. Scientific priority is determined by who publishes an idea first; great scientific races occur in which competing laboratories rush to publish their results before their competitors can do likewise. Although this is not always beneficial (incomplete information and incorrect results occasionally get published as a result of such competitions), the incentive to publish quickly does speed the progress of science. Once the information is generally available, it becomes part of the education process for other scientists and the cycle begins anew.

New information, even new information published in reputable journals, is not automatically accepted, however. It is first subjected to the critical evaluation of the scientific community. This evaluation process usually begins informally, when scientists discuss their newest results with their coworkers. More formal evaluation comes during the process of peer review, which is required for publication in most reputable journals: a panel of anonymous reviewers who are all scientists working in the same area as the authors of the submitted paper must approve the publication of the paper before it is accepted for publication by the journal. Finally, every scientist who reads the journal article carefully subjects it to the same critical evaluation process.

The standards by which new scientific information is judged are remarkably constant across scientific discipline lines. These standards are learned by experience, both experience in reading the literature and experience doing science. Some of their general features are discussed in the next section.

Scientific Standards: Good Science, Bad Science, and Pseudoscience

When evaluating a new piece of scientific information, a scientist will try to consider both the implications of the information and the way in which it was obtained. Much of this should be available in the research paper that formally presents the new information. Research papers from many different scientific disciplines share a common format designed to make the reading and review of these papers as efficient as possible. The sections are usually arranged as follows:

1. Title.
2. Authors' names and institutional affiliations.
3. Abstract: a one-paragraph summary of the work.
4. Introduction: a short explanation of the scientific context of the work; a rationale for exploration of the scientific problem.
5. Materials and Methods: A list of the sources of all experimental materials and a description of the experimental methods employed.
6. Results: A description of the results of the experiments/observations/calculations; should be acccompanied by as much of the raw data as is practical to present, along with summary tables and figures.
7. Discussion/Conclusions: A description of the implications of the results; often contains speculative material.
8. References: A list of the publications cited in the text, along with attribution for unpublished material; every scientific assertion that is not either based on general knowledge or based on the experimental results discussed in the paper must have a reference to back it up. Isaac Newton need not be cited for his gravitational theories, but unpublished data from a colleague or recently published data from a competitor must be cited appropriately.

So, what features distinguish good science from bad science? Some features can be found in the research paper itself. Are the calculations correct? Have appropriate statistical methods been used in the data analysis? Are the results statistically significant, and if so, by how many standard deviations? Are the assertions made in the discussion consistent with the data presented in the paper? Is the series of experiments/ calculations/ observations described sufficient to solve the problem unequivocally, or are there logical flaws or omissions that would lead to the possibility of other interpretations of the data? Were adequate control experiments performed? Were the experiments performed in such a way as to exclude investigator bias (for example, the use of double blind methods in medical experiments)? Is there sufficient detail in the methods section that a scientist versed in the methods described would have a reasonable chance of being able to repeat the experiments/ observations/ calculations? Is the quality of the data shown high, or does it look as though the data weren't very clean? Are the results interesting, or did the authors spend a lot of time working on a problem that nobody else cares about or ever will care about? Different scientists reading the same research paper may have different answers to these questions: some of this process is admittedly subjective.

In a new area of science, it is not unusual for research reports from different laboratories to conflict. Science at the cutting edge is not always clean and conclusive. This reflects both the inevitable existence of error and the possibility that all of the aspects of the problem may not yet be well understood: experiments that attempt to explore similar problems may in fact be exploring totally

different aspects of a problem, and their results will appear to conflict until more experiments are done. Much of the scientific process involves the clarification of conflicts in the literature and the refinement of old ideas about the world based on new data.

Most published scientific papers probably fall somewhere on the scale between good science and ho-hum science. Some studies are more important and far-reaching in their implications than others; some have better data and fewer flaws than others; but, most of the time, they reflect an honest attempt to do good science. There are exceptions to this general rule, however. They fall into two general classes: deliberate fraud and pathological science.

Cases of documented deliberate fraud are rare and tend to make the headlines. In the field of immunology, the most famous example is that of Dr. William Summerlin, a scientist who colored black patches on his white mice in order to make it appear that they had accepted skin transplants from completely unrelated black mice. Another example comes from the field of psychology: Sir Cyril Burt, who in his time was one of the most important and influential scientists in his field, apparently fabricated thirty years worth of data purported to come from intelligence testing of identical twins. It is hard to understand why a scientist would commit fraud: the nature of science is that fraud will eventually be discovered, and the fame that the perpetrator sought will turn into notoriety and destroy his scientific reputation. Such things do happen, however, and slow the progress of science. Burt's fabrications affected psychology until after his death; Summerlin's fraud was discovered rather quickly and did less damage. Fortunately, it appears that such situations are rare.

A more subtle form of bad science is known as pathological science, after the designation of the man who first clearly identified its symptoms, the physicist Irving Langmuir. This form of bad science probably reflects self-deception (at least at first) on the part of the scientist rather than deliberate fraud. The recent controversy over Fleischmann and Pons' report of a process that apparently allowed nuclear fusion (the process that powers the sun) to occur at room temperature in a test tube can be used to illustrate pathological science. The symptoms, and their manifestation in the case of cold fusion, include:

1. Pathological science is generally performed by scientists who are not experts in the field in which they are trying to work . Fleischmann and Pons are electrochemists, not nuclear physicists, and had very little of the scientific background needed to really understand nuclear fusion.

2 The size of the effect is just above the threshold of detectability. This certainly was the case for cold fusion. Pons and Fleischmann detected a few watts of energy coming from their cold fusion cells--a factor of ten less energy would have been undetectable, while a factor of ten more energy would have been obvious to anyone. They also detected a few neutrons, indicating a nuclear process--a factor of ten fewer would have been unseen, a factor of ten more would have been obvious. These simple facts convinced most scientists at the outset that cold fusion was invalid--the amount of energy disagreed with the expected number of neutrons by a factor of 100 trillion, yet both were just above the threshold of detection.

3. The size of the effect is independent of the size of the cause. With cold fusion, doubling the size of the cell did not change the amount of heat or number of neutrons. It was later noted that the obvious control experiment (removing the suspected cause of the effect entirely by using regular water, whose

normal hydrogen atoms should not undergo fusion, instead of water in which the hydrogen atoms had been substituted with deuterium atoms, as in their experiment) had not been done. When the control experiment was finally performed, the effect did not vanish, suggesting that there was something wrong with their interpretation of the effect or that there was something funny about the effect itself.

4. Essential information about the experiment is missing. Pons and Fleischmann never published their experimental protocol, claiming that patent obligations and, later, the press of experiments, kept them from doing so. When pressed by the scientific community, they sent protocols to individual investigators trying to replicate their results, but the protocols were insufficient. Pons and Fleischmann then offered ad hoc explanations for these failures of replication; these also failed to resolve the problems. Ad hoc explanations are another of Langmuir's warning signs.

5. The effect is totally unexpected and very important; it contradicts the available theoretical models. Cold fusion would have been a cheap, clean source of vast amounts of energy had it really existed; thus, it was a highly important effect. The possibility of its existence was in direct contradiction to the theoretical understanding of nuclear fusion current at the time (which is still the accepted understanding, incidentally), yet Pons and Fleischmann offered no new scientifically acceptable modifications of nuclear fusion theory to explain their results.

6. The number of believers soars initially to include about half of the scientific community, then declines rapidly as negative experiments pile up. It is hard to document this precisely in the case of cold fusion, but certainly the tone of editorials about it in *Science* and *Nature*, the two major general science journals, changed from initial interest, confusion, and excitement to disbelief and outright rejection quite quickly, reflecting the discussions occurring among scientists at the time.

A final topic that belongs in any discussion of bad science is the topic of pseudoscience. Pseudoscience is not science, but purports to be science. Examples include astrology, creation science, psychic surgery, and other fringe and paranormal beliefs. Pseudoscience can be distinguished from science by its inability to survive well-controlled experimental tests and by its dependence on the word of an "authority" (whether a person or a text) rather than experiment/ observation/ calculation. It is unfortunate that pseudoscience appears to be as attractive or more attractive to Americans than science is: *The National Enquirer* certainly has a much larger readership than does *Scientific American*, or, for that matter, *The Skeptical Inquirer*, a publication that devotes itself to scientific testing of claims of the paranormal.

Rationale for Teaching the Concept

The concept of the scientific process is not one that lends itself readily to being taught directly. Its components, however, should be taught indirectly every time any scientific concept is taught. The process itself can be incorporated into any situation in which students are expected to do hands-on science. In addition, the reasoned skepticism of a scientist approaching a new piece of information can be made a part of students' approach to scientific thinking: teaching students to ask "How do we know?" rather than "What do we know?" teaches them the essence of science. Allowing students to approach a problem as a scientist might, by educating themselves about it, formulating the problem more precisely, thinking of experiments/ observations/ calculations that would help to solve it, doing those tests, refining

the problem some more, then ultimately presenting their work to others, helps them to understand that science is not a dead pile of facts in a textbook, but rather a living, dynamic, challenging, and exciting process. Students must learn the fundamental concepts of science, because a solid scientific knowledge base is essential for understanding not only modern science but also more general issues, such as the problems of pollution, overpopulation, resource depletion, and global warming. If this knowledge base is acquired, at least in part, as a component of an active scientific problem-solving process, students will understand it better and probably retain it longer than if they simply memorize facts from a textbook. The students that go on to do science will be better prepared for it by such experiences; those who go on to do other things will have a richer appreciation of the strengths and limitations of science. They will also have honed the thinking skills required to distinguish good science from bad science and pseudoscience, which is in itself an important and desirable result.

Suggested Applications

The scientific process can probably be best conveyed by having the students approximate doing science in an inquiry learning situation with the modifications suggested in the Suggested Applications: General Considerations section of this guide. Many different topics could be covered by such an approach, including those suggested in the other concept papers in this series.

As an example, consider the problem of energy policy. This example would probably be appropriate for grades 6-8. This topic illustrates a number of the general concepts in this series, including systems (the Earth as a closed system with finite resources); change (rates of energy consumption, both by nations and by machines; rates of energy production; rate of growth of energy use); and scale (magnitudes of energy use, from that used by a light bulb to that used by a nation.) Students could be told a few relevant facts to get them started, including the current fraction of oil used in the U.S. that is produced domestically; the amount of oil used every year by the U.S. and the rest of the industrial nations; the proven oil reserves for different nations of the world; and a brief history of the Persian Gulf war. They could then be asked the question "Is there a problem here?" They would then have to go through a set of group tasks:

1. Determine if a problem exists. In this case, they should be able to see that we depend heavily on foreign oil; that if the status quo continues, over a fairly short time we will depend even more heavily on foreign oil; that this situation is militarily as well as economically dangerous for the U. S.; and that there is, indeed, a problem. This corresponds, roughly, to steps 1-2 of the scientific process.

2. Create an exact statement of the problem. We are using up a nonrenewable resource and endangering our national security in doing so; we need to find domestic alternatives to foreign oil or to find ways to use less oil. This corresponds to step 2 of the scientific process.

3. Generate possible solutions. Exploration, conservation, alternative energy sources: these are some pretty standard suggestions for solving the problem. This step corresponds to step 3 of the scientific process, with a dose of step 1 thrown in: students will have to educate themselves more in order to come up with possible solutions.

4. Evaluate the possible solutions. Each suggested solution should be evaluated in terms of cost and feasibility. This step, again, combines steps 1 and 3 of the scientific process.

5. Test the possible solutions directly. Here are some suggestions:

•Students should be organized into groups, each of which will study a different suggested solution.

•Students studying solar energy should do some experimental work with solar cells to look at their efficiency ; they should then calculate the cost of land, materials, and so on needed to replace an oil-fired power plant with a solar installation; the same could be done for students advocating wind power and other alternative energy sources.

•Students studying conservation should look experimentally at some conservation approaches. For example, they could change the thermostat setting at home for a while and see how much energy they save by doing so, or test the energy use of a more energy-efficient light bulb, or compare the energy efficiencies of the cars belonging to the families of their classmates. How much energy does each energy-saving measure really save? What kind of effects do different conservation measures have on their lifestyle?

This step corresponds to steps 4-5 of the scientific process.

6. Communicate their results. This could be done in a seminar format (oral reports), a poster session format (each group makes a poster detailing their experiments, their results, and their conclusions, and then everyone reads everyone else's posters), or a journal format (reports are written, bound together in magazine form, and then distributed to each member of the class.) A good, recent reference for this topic is:

Hubbard, H.M. (1991). The real cost of energy. Scientific American, 264, 36-42.

Scientific Standards

Some sense of what good science is and is not could be conveyed by using an inquiry-based approach to evaluate pseudoscience. No sophisticated knowledge base is needed to understand some forms of pseudoscience. Astrology, for example, can be subjected to meaningful testing quite easily. Some suggestions for associated activities include:

1. Compare the forecasts of different astrologers for the same person on the same day; note similarities and differences.
2. Pass around copies of the forecasts for the day before without the labels (so that nobody knows which is for Scorpio, which for Cancer, and so on.) Can people correctly pick the forecast that was supposed to apply to them? Do this for a number of days in succession, and see if they can pick their own forecast at a rate significantly higher than that predicted by chance.
3. Find out how astrologers make forecasts. Is there a standard method, or is it unreproducible from person to person?

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4. Find out the theoretical basis for astrology. Does it square with what is currently known about the forces that operate in the universe, or is it scientifically inexplicable?

For other possibilities in pseudoscience testing, see back issues of *The Skeptical Inquirer* and the following books:

Gardner, M. (1957). Fads and Fallacies in the Name of Science. NY: Dover Publications, Inc.

Randi, J. (1982). Flim-Flam. Psychics, ESP, Unicorns, and Other Delusions. Buffalo, NY.

Scale

What is the concept of scale? Simply put, the idea of scale refers to the naturally occurring range of magnitudes of such measurable properties as distance, time, density, and speed. Scientists of different persuasions study everything from the behavior of the elementary particles that make up all of matter to galaxies that are unbelievably distant from the Earth. Thus, scientists in different disciplines deal with scales with which most people are unfamiliar. For example, timescales that can be experienced directly by humans range from around a millisecond to a human lifetime. On the other hand, scientifically important timescales range from incredibly minute fractions of a second to billions of years. Similarly, the distance scale used by scientists is much larger than that directly experienced by people: scientifically relevant distance scales range from less than a trillionth of a meter to twenty billion light years. One of the best ways to illustrate this is to simply list phenomena that occur from one extreme of a quantity to the opposite extreme. This has been done in Table I for distance and in Table II for time. Similar scales can be described for such scientific things as volume, density, viscosity, velocity, earthquake magnitude (the Richter scale), and other phenomena to which numbers can be attatched. Nonscientific examples of scale include the scales of population density (ranging from the average population density of most of South Dakota to the population density of cities like Tokyo) and debt (which, in the U. S., ranges from a penny's worth of postage due to the three trillion dollars of the national debt.) The idea of scale is also familiar to any student who has ever picked up The Guiness Book of World Records: this book's purpose is to publicize the extreme magnitudes of measurable quantities (world's tallest man, world's shortest man, and so on.)

A second feature of the concept of scale is the use of the term to describe a context. The human scale, for example, is the scale of the world that humans directly perceive. Distances range from a fraction of a millimeter to the distance to the farthest point to which we normally travel; times range from milliseconds to around one hundred years; the range of colors that we see goes from violet to red; and so on. The way that we think about reality is conditioned by our everyday experiences at our own scale. In fact, the scale that we perceive as normal changes over a lifetime. The world that a toddler sees is quite different from the world as seen by a six-foot tall adult man. Chairs that the man finds comfortable are formidable climbing challenges to the toddler; windows that a man sees the world through present only sky to a toddler; and so on.

As we move farther from the familiar human scale, the world becomes less and less recognizable. The forces that operate and the phenomena that are important become vastly different. This can be illustrated by looking at the features of scales that are progressively more different from the human scale.

At the scale of insects, for example, the force of gravity becomes less important than it is at the human scale. Human beings are highly aware of the force of gravity. It holds us to the ground even in high winds; it makes the last months of pregnancy uncomfortable as a woman's center of mass shifts into a position that the muscles of her back and abdomen do not support well; it makes the sport of weight-lifting possible. A human bodybuilder can, with steroids and training, hope to lift up to 500 pounds, about three times his own weight. Ants, on the other hand, can carry things up to 50 times their own weight.

Similarly, in all of human experience, no person has ever walked on water without artificial or supernatural assistance, as the surface tension of the water under a person's feet will not support the person's weight. Water striders do it with ease, as the force of gravity acting on their relatively smaller mass is not enough to overpower the surface tension of the water. The molecular properties of water that result in surface tension are thus more important at the scale of an insect than they are at the human scale. Differences such as these that are a feature of a change of scale are known as scaling effects.

Scaling effects vary depending on the phenomena observed. The giant insects in science fiction horror films are, sadly, not really possible for scale-dependent reasons. The ability of their scaled-up limbs to support weight would not counterbalance the effects of gravity: the strength of a support increases as a factor of its cross-sectional area, while the volume (and therefore the mass) of an object, when scaled up, increases as the cube. The legs of a giant grasshopper, for example, would collapse the first time it stood up. This problem, incidentally, also applies to the rest of its skeleton-the materials used and the design of the exoskeleton would have to be radically changed to support the giant grasshopper's bulk.

The change in scale represented by the fictional giant grasshoppers is relatively small: real grasshoppers are a few centimeters long, while Hollywood 's giant grasshoppers were perhaps 10 to 100 meters long. The factor by which they were scaled up was at most 10,000X. This isn't much when it's compared to the range of distances found in nature, as a quick reference to Table I will show.

At scales more different from our own, scale effects become even more pronounced. At the scale of bacteria (a factor of about 1,000,000X smaller than we are), for example, the motions of individual molecules are important, so important that they can be readily detected with a microscope. The wiggling of microscopic specimens suspended in water is known as Brownian motion. It is a direct result of the random thermal motion of molecules surrounding the specimen. At temperatures above absolute zero, all atoms and molecules are moving in a number of different ways: they rotate, they vibrate, and they move from place to place (they translate). Every molecule in a liquid, for example, is moving around in random directions. If lots of molecules bang into a bacterium from one side at the same time that only a few bang into it from the other side, the bacterium will move a small distance-but a distance that is readily apparent to the observer using the microscope. Needless to say, the movement of individual molecules is not nearly as important at the human scale as it is at the bacterial scale.

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At the bacterial scale, other unusual effects can be seen as well. Gravity, for example, is much less important to a bacterium than it is to us. If a flask containing a culture of E. coli in nutrient broth is left in the refrigerator for a day so that the bacteria are too cold to swim, they will gradually settle to the bottom, a process that takes hours. It certainly wouldn't take a person hours to fall a distance of a few inches in water. In addition, the water that the bacterium experiences has different important properties than it does for us. The water "feels" more viscous to the bacterium. Water molecules in a liquid are connected to each other by hydrogen bonds, which are relatively weak and break and reform constantly as the water molecules move thermally. To move, a bacterium must push against this interlocked network of hydrogen-bonded water molecules, a process that is more difficult for it than for us because of the relatively smaller force that it can exert. In fact, the surface of the water represents an impenetrable barrier for the bacterium, as the force that it can generate by spinning its flagellae is much smaller than that needed to break the water's surface tension (which is itself a direct consequence of the hydrogen bonding between water molecules in the liquid).

If one descends further, to the scale of the atom, conditions become even more different from those prevailing at our scale. Here, the laws of quantum mechanics become important. Instead of being smooth, things are quantized: for example, an electron moving in an atom can have only a few permitted energies, and all other energies are forbidden to it. If this were the case at our level, a car, say, could go five miles an hour or fifty miles an hour, but couldn't go, say, forty miles an hour; and the transition between five and fifty miles an hour would occur instantaneously, with no intermediate speeds. In addition, the uncertainty principle becomes important: you can't know both the position of a particle and its speed and direction of motion at the same time. Another strangeness is that the world at this level is mostly empty space: electrons can be best thought of as a buzzing fog around the atomic nucleus, and the size of the nucleus relative to the size of the atom can be compared to that of a ping-pong ball in the Astrodome.

Clearly, our intuition and our perception of reality fail us at small distances. They also fail us at the largest distance scales. Consider the fundamental theorem of plane geometry: parallel straight lines will never intersect. Here, "straight line" means that the line connects any two points on it by the shortest distance between them; "parallel" means that a line perpendicular to one will also be perpendicular to the other. This fundamental theorem seems perfectly obvious, natural, and hardly worth stating (except by mathemeticians). On large distance scales, however, it is wrong: parallel lines meet at some astronomically large scale. Our three-dimensional space is curved, although the curvature is so slight that one needs to examine billions of light years of distance to detect it.

To illustrate this point, one can consider a small ant on the surface of a large sphere. She would believe that the surface was flat (just as, for most of human history, people have thought that the Earth is flat.) Suppose this ant explored two lines on the sphere, corresponding to the north-south lines given by 120 degrees longitude and 100 degrees longitude, as illustrated in Figure 1. These two lines always connect any two points by the shortest distance between them, and they have the same perpendicular (the equator); they are thus two parallel straight lines. Yet they intersect at the poles. Similarly, in our universe, it is believed that two parallel straight lines will eventually intersect. In fact, if you travelled in a perfectly straight line, without turning around, you would eventually reach your starting point!

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As illustrated by the preceding examples, the world is very different at different scales, and at the most extreme scales, normal human intuition can be entirely wrong. The concept of scale and an appreciation of the differences between events occurring at different scales is thus important for an understanding of science. Scientists working at different scales gradually develop an intuitive feeling for the scale context of their work. A quantum mechanic and an auto mechanic will thus have different, but in a way equally valid, appreciations of the world.

Rationale for Teaching the Concept

One of the most important features of science is that it helps us to better define our place in the universe. A proper appreciation of the concept of scale and of the differences that ensue with a change of scale will expand a child's understanding of where she fits in and of the vast array of other possibilities that exist.

Suggested Applications

The concept of scale can be illustrated in a variety of ways. Each of the applications suggested below could probably be adapted appropriately for use at most levels. In addition to the direct applications suggested here, the concept of scale can be worked in indirectly every time a scientific phenomenon that occurs at a scale different from our own is studied. When microorganisms are studied, for example, the sizes and features of the microscopic world can be compared with the features and sizes to which humans are accustomed.

1. Students could make lists similar to those in the tables for a variety of different phenomena. Students could be encouraged to come up with the numbers themselves through library research and measurements of their own. For example, you could ask students to come up with a distance scale that illustrates the range of distances that they themselves have experienced and illustrate it with examples; it could then be physically modeled, as in application 2.

2. Have students physically model different scales. For example, a timeline is a good way to model the geologic timescale. If it is done reasonably accurately, it gives students a good feeling for how long the earth has been around and how short a period of time humans have been around in comparison. The scale of the solar system can be modeled by students if you give them a pea, tell them that it represents the Earth, and then ask them to tell you how they would represent the other planets, the moon, and the sun and to tell you where they would place these objects relative to the pea. These physical demonstrations give students an intuitive feeling for the magnitudes of scientific phenomena, particularly if they have to work out the features of the physical model themselves.

3. A third way to look at scale would be by having students look at the effects of small changes in scale. They could observe the animals directly to determine the kinds of differences that exist between their scale and that of the animal and then imagine how the world would look from the point of view of the animal. They could draw pictures of the world as seen from the animal's point of view, write stories about how it would feel to be the size of the animal, and so on.

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4. Have students do some engineering to look at scale effects (strength of supports, types of materials employed, and so on.) A visit to a building site or two would amplify their understanding of the different materials required to make buildings on different scales (the materials for a house are different from those needed for a skyscraper, for example.) An architect or engineer could also be brought in to talk about scale effects and design.

5. Have students design their own system of units and construct scales using them. This deepens their understanding of the use of units and of the human scale at the same time.

Legend for Table I: This table lists phenomena that illustrate the range of distances important to scientists. The length of one meter has been arbitrarily chosen as the starting point because it is squarely in the middle of the range of lengths humans experience, being twice the length of a newborn baby and about half the height of an adult.

Table I

Going down in length from one meter

1 meter (10^0 meters):	the height of a three year-old child
1 centimeter (10^{-2} meters):	the radius of a penny; the length of a carpenter ant
1 millimeter (10^{-3} meters):	the diameter of a sewing needle
1 micron (10^{-6} meters):	the diameter of some kinds of bacteria (sizes range from 0.1 microns to 10 microns)
1 nanometer (10^{-9} meters):	the diameter of the DNA molecule
1 Angstrom (10^{-10} meters):	the diameter of the hydrogen atom (ground state)
1 fermi (10^{-15} meters):	the size of a proton

Going up in size from 1 meter

10 meters:	30 feet; the depth of a middle-class suburban front lawn
100 meters (10^2 meters):	the (approximate) length of a football field
1 kilometer (10^3 meters):	5/8 of a mile; a short walk for a healthy adult
1000 kilometers (10^6 meters):	the distance from San Diego to San Francisco, or Washington, DC to Boston
10^9 meters:	three light seconds; roughly, a round trip to the moon
10^{12} meters:	the size of Jupiter's orbit
10^{16} meters:	one light year; a quarter of the distance to the nearest star
10^{26} meters:	the distance to the farthest observed galaxy

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Legend for Table II: The range of scientifically relevant timescales has been illustrated here, starting again from the human scale.

Table II

Going down from 100 years

100 years:	the (approximate) present maximum human lifespan
10 years:	the age of the average fifth-grader
1 year:	the (approximate) time of human gestation
1 month:	a lunar cycle
1 day:	the lifespan of the adult form of the mayfly
1 hour:	the length of a college lecture
1 minute:	two TV commercials
1 second:	a heartbeat; the distance Dan Quayle is from the Presidency
0.1 second:	an eyeblink
1 millisecond:	a high speed camera exposure; a hummingbird wingbeat
1 microsecond:	the time it takes light to cross a football field
1 nanosecond:	the time it takes light to go one foot
10^{-24} seconds:	lifetime of the Z particle (and most other strongly interacting particles)
10^{-35} seconds:	the time in which the universe expanded by a factor of 10^{100} during the period of inflation that followed the Big Bang
10^{-43} seconds:	the earliest time in the universe that physics can explain; the time before which the concepts of time and space had no separate meaning (for a good explanation of this, see the Hawking reference in the bibliography)

Going up from 100 years

1000 years:	the length of time since the Christianization of Russia; one-fifth of the lifetime of a bristlecone pine
10,000 years:	the total length of human civilization
1 million years:	the length of the existence of humans as a species
1 billion years:	one quarter the age of the Earth
10 - 20 billion years:	the approximate age of the universe
10^{35} years:	(predicted) lifetime of the proton
10^{73} years:	(predicted) lifetime of a typical black hole
$10^{10^{120}}$:	time required for the spontaneous creation of a universe, according to a recent theoretical paper (note that at this scale, no units of time are necessary)

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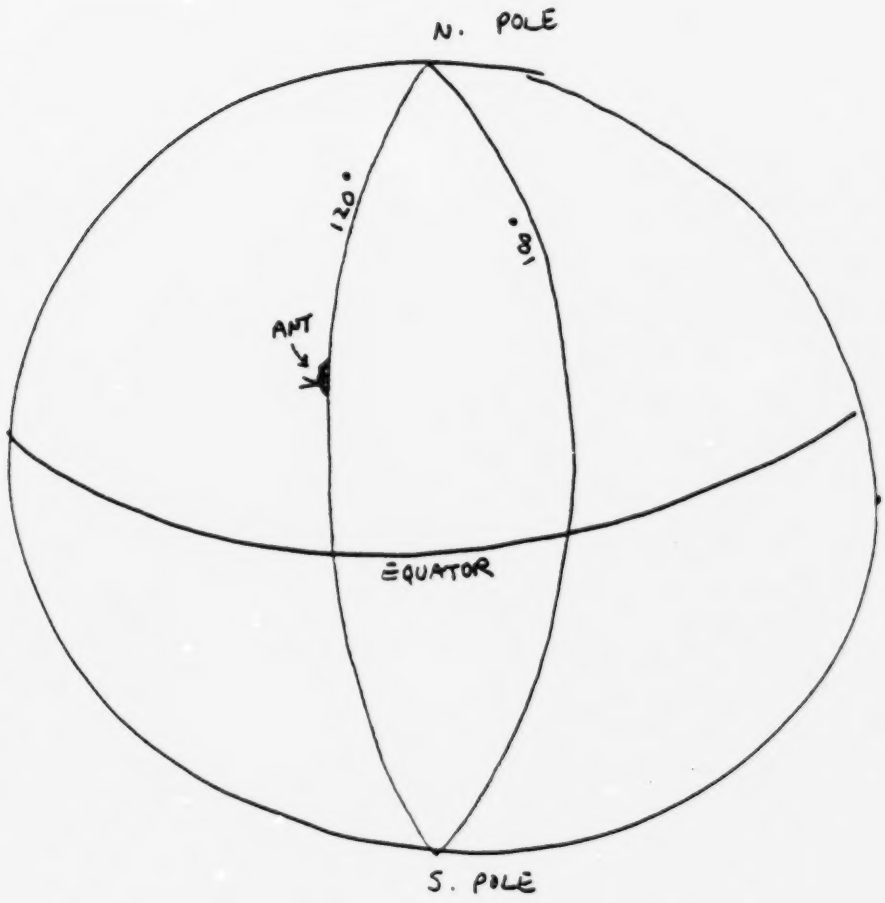
Figure 1

An Ant Traces Out Longitude Lines on a Sphere



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Models

A model is a simplified imitation of a thing or process. Models are used both in science and in the rest of human endeavor to better understand interesting things, to communicate their salient points to others, and to try out new ideas in a simplified way. To be useful, models must simulate the real-world thing that they represent in such a way as to match its behavior in a relevant way but make testing and prediction easier. One common simplification involves changes in size. For example, physical models of atoms are the size of childrens' blocks, but connect to each other at the same angles that the atoms use for bonding and are built to represent the relative sizes of the different kinds of atoms. The scale models of buildings used by architects are small enough to move around in a model landscape. Maps and globes are much smaller than the territory that they represent. Another common simplification is a change in timescale. Processes that occur too quickly to be amenable to study can be modeled at a slower speed; slow processes can be simulated at a higher speed. A third important type of simplification is the exclusion of all but relevant variables. Highway maps, for example, do not include the resource information found on geologic maps, as this information would only add visual confusion to the perplexities faced by a lost driver. A blueprint of a house specifies the dimensions for each room but doesn't specify the Formica pattern for the countertops in the kitchen. The blueprint is thus a relevant model for the house to the architect but fails to specify everything relevant for the interior decorator. By inclusion of only relevant variables, models can be tailor-made for every application.

Models can be physical, conceptual, or mathematical. An example of a physical model would be an architect's blueprint, a scale model of an airplane, a molecular model of a new compound, or a toy train set. Physical models are probably the easiest to understand, as there i s something there to see, touch, and experience.

The second type of model is the conceptual model. Examples of conceptual models include thinking about the universe as a series of interconnected bubbles, or comparing the flow of traffic to the flow of a liquid through pipes. Conceptual models can be thought of as metaphors. The heart is like a mechanical pump; the situation in the Persian Gulf at the beginning of August 1990 was like the situation in Europe when Hitler reoccupied the Rhineland; the shape of blood vessels in the body is like the shape of the branches of a tree: all of these comparisons create conceptual models in which the salient features of the first member of each pair of items can potentially be used to understand the salient features of the second member of the pair.

The third type of model is the mathematical model. Mathematical models are used to mathematically simulate real-world processes: economic forecasting, weather prediction, and understanding the nature of the earliest moments of the universe all depend upon mathematical models. Such models consist entirely of mathematically defined relationships between the important variables involved in the behavior of the real-world system. Mathematical, physical, and conceptual models are used extensively by scientists and nonscientists alike.

In science, there is perhaps no better-known physical model than the double helical representation of the molecular structure of the DNA molecule. DNA (deoxyribonucleic acid) serves as the genetic blueprint for every organism that is built of cells (some viruses use RNA, a close relative of DNA, as their genetic material.) In the 1950s, James Watson and Francis Crick correctly deduced its structure with the help of

X-ray crystallographic data provided by Maurice Wilkins and Rosalind Franklin. Using the X-ray data that showed that the molecule contained a helix as an essential element and their knowledge of the principles of chemical bonding, they built a physical model of the DNA molecule that satisfied all of the available data for its structure. The physical model (illustrated in Figure 2) immediately suggested to Watson and Crick a conceptual model that explained how DNA could direct the formation of copies of itself (illustrated in Figure 3). This conceptual model suggested that the DNA double helix first uncoils into single strands and that each strand is then copied by enzymes to generate two new identical double-helical DNA molecules, each of which contains one newly synthesized strand and one old strand. Subsequent experiments proved that this was indeed the case. This was of vast importance. A key feature of the properties of genetic material is that it has to be capable of self-replication: every time a cell divides, each new cell receives a complete copy of all of the genetic material that the parental cell possessed. A measure of the power of physical model-building in this example is the ease with which the physical model could be interpreted to enhance the understanding of the DNA molecule's function.

A second situation in science in which model-building has been critical is the case of the Big Bang, the event that describes the formation of the universe. Modeling the Big Bang has been a conceptual and mathematical exercise: this is not a system that lends itself to physical modeling, as physicists don't make new universes every day in the lab. Mathematical modeling, however, has led to predictions that are physically verifiable. For example, George Gamow first predicted that the Big Bang's initial explosion would leave a signature of sorts, a uniform background of microwave radiation present all through the universe. This mathematical prediction was made and refined in the1950s; in 1964, Penzias and Wilson detected this microwave background using a radiotelescope, an experiment for which they later received the Nobel Prize. Thus, in this case, a conceptual model led to a mathematical model, which, in turn, led to an experimentally verifiable prediction. Much of modern physics has proceeded in exactly this way: conceptual and mathematical modelling tells the experimental physicists what to look for.

Yet another famous model in science is the concept of plate tectonics. It had been long known that there were similarities in geology between such widely separated regions as Africa and South America. In the early twentieth century, Alfred Wegener formulated the hypothesis that the continents did not always occupy the same places that they do at present, but rather had drifted across the face of the globe over time. Thus, at one time, Africa and South America were physically linked, and during that time, geological phenomena had occurred that affected each of them identically: the history of their contact was therefore written in the rocks. For many years, Wegener's conceptual model was not accepted, as nobody could think of a mechanism to explain continental movements and the whole idea seemed rather far-fetched. Finally, though, a new form of data emerged, a way of testing rocks to see the magnetic field conditions present during their formation. The magnetic field of the earth periodically reverses, and these reversals can be detected by study of the rocks and dated by using other methods of determining the age of the rocks. Paleomagnetism data provided unequivocal evidence for the movement of the continents, and Wegener was vindicated. Working through the implications of continental drift provided geologists with new explanations for old phenomena, including the locations of regions of volcanic and earthquake activity and the processes of mountain building. This conceptual model, the theory of plate tectonics, has thus greatly enriched the discipline of geology.

Model-building in science is not always as successful as it was in the three examples just mentioned, however. Many systems do not lend themselves to direct modelling. For example, the development of

treatments and an eventual vaccine for AIDS has been hampered by the fact that only humans can be infected by HIV (the virus that causes AIDS) and proceed to develop AIDS. In many disease states, the human condition can be directly simulated by an animal model. For example, diabetes was modeled in dogs: dogs whose pancreases have been removed become diabetic, and treatments for diabetes (such as injectable insulin) were tested in dogs before being tested in humans. In the case of AIDS, though, only an indirect animal model is available: monkeys have a virus similar to HIV known as SIV, and SIV infection in monkeys has been used to model HIV infection in humans. Because SIV and HIV are not identical, however, testing of antiviral therapies and vaccine development have been heavily dependent on human volunteers, creating a situation rife with ethical problems and experimental limitations.

Even when a physical model is available, there can be other limitations. For example, the correspondence between the model system and the phenomenon being modeled may be inadequate or misleading. Biologists, for example, routinely test pharmacologically active compounds in animals before the FDA allows their use in people. This is supposed to protect humans from unpredicted side effects of new drugs and to ensure that the new drugs are effective for the condition for which they will be prescribed. Yet animals are not always perfect models for humans. The drug thalidomide, for example, was tested for safety in rats before it was approved as a tranquilizer in Europe for humans. There were no ill effects in rats, but it caused severe birth defects in humans who had been exposed to it as fetuses in utero. Imprecision of fit between the model and the real-life thing is a frequent limitation in the use of a model.

There are thus limits to the use of model-building in science. Understanding the uses and limitations of model-building is also important in other, nonscientific, areas. For example, the budget process that the Federal government goes through every year is highly dependent on the mathematical models of economists. Forecasting the Federal deficit, for example, depends upon knowing how the economy will respond to events that could occur over the next budget period: war, decline in consumer confidence, increases in the price of energy, and so on. Curiously enough, forecasts emerging from the Executive Branch rarely match those from the Congress (particularly when the Congress and the White House are controlled by different political parties.) This reflects several common limitations of model-building. The U. S. economy is highly complex and modeling it demands information on a very large number of variables. If the numbers fed into the computer models are incorrect, or reflect biased estimates, then the resulting projections will differ both from reality and from projections made by a group with different biases. The technical term that describes this problem is GIGO: garbage in, garbage out. In addition, the relationships among all of the variables governing the behavior of the U. S. economy are not all precisely known. Thus different economic models which treat these relationships differently will arrive at different predictions even when the same data are fed into them. It is very difficult to accurately model such complex systems: modelling the behavior of the Earth's atmosphere well enough to generate reliable weather forecasts is another case in point.

Weather forecasting is dependent on mathematical models that describe the behavior of the Earth's atmosphere. Weather data from hundreds of weather stations across the world are fed into huge computers every few hours, and the changes occurring over that time period are noted. Historical information about the patterns of change that have occurred in the past and theoretical descriptions of the behavior of different weather systems have been used to generate computer programs that relate the patterns of change occurring on a given day to each other and predict the likelihood of the occurrence of particular forms of weather in a particular place in the near future. The complexity of the system and

the sheer number of variables and amounts of data involved combine to make long-term predictions less accurate than short-term predictions. Thus, forecasters can predict tomorrow's high temperature within a degree or three, but the extended forecast for the next month will only predict that the average temperature will be higher (or lower) than normal. The mathematical models that describe the behavior of the atmosphere are constantly being refined, and so weather prediction has become considerably more accurate over the past twenty or thirty years.
The use of physical, conceptual, and mathematical models is common in both scientific and nonscientific fields. Understanding how models are made, how they can be used, and the potential pitfalls of model systems is important for all educated adults. Many of these ideas can be addressed at a child's level, as described below.

Rationale for Teaching the Concept

The concept of models is potentially very easy to bring down to a child's level: they play with models every day. Their models are called toys. Blocks are models for building materials; a child that can build a stable tower has worked out some of the most basic engineering principles. Playing house allows children to model adult behavior and replicate the actions of their adult role models. Video games model such wonderful experiences as flying an airplane or killing evil creatures in the sewer system. The only type of model that children do not come to naturally is the mathematical model, and even this concept could be introduced to them in at least a simple form.

Working with models in a science context is a good way to bring scientific concepts down to a child's level. For primary age students, physical models are the most appropriate; for older students, conceptual and mathematical models can be worked in. If they have to use simple circuits to build a working radio-controlled model car, they'll pick up a better understanding of electricity along the way; building a better protection device for eggs than a styrofoam egg carton teaches some basic physics as well; building a better paper airplane teaches some aeronautics.

Making and using models can also help develop a child' s scientific process skills. Being given materials and an unfamiliar problem to solve fosters higher-level thinking skills, if done well (fosters confusion and irritation, if done badly). Refining their models to fit new data helps them to understand that the scientific process is full of false starts and blind alleys but that progress can eventually be made nonetheless.

In building and using models in a scientific or technological context, children can develop an excellent feeling for what doing science is all about. The study of models lends itself to creativity, curiosity, and the ability to try new ideas and succeed in generating new insights.

Suggested Applications

Model building is accessible to every age group. The science may be worked in around the model-building, or vice versa. The strategy of problem-based learning can easily be employed to teach this concept. If the students were given a challenge (figure out how to design a paper airplane that could stay in the air for twenty seconds after being thrown from a third-floor window, for example) they could be encouraged to go find the relevant science on their own. Facilitated by a teacher, this would become an exercise in the practical application of the principles of aerodynamics to model planes. The possibilities listed for the

younger grades could also be used for older children in greater detail and depth.

For grades K-2:

Blueprints: making and reading
Maps and mapmaking
Paper airplane contests
Terraria
Aquariums
Building bridges

For grades 3-5:

Dollhouse construction (with working plumbing and electricity?)
Building a better model boat
Electronic doodads-Radio Shack science
Robotics with electronic Legos
Designing a Mars colony

For grades 6-8:

The egg drop experiment: building better packaging
Geologic maps: making and using
Orienteering
Fun with molecular models: both physical and computer-generated
Simple mathematical modelling of physics concepts; tie it in with physical experiments performed first

Figure 2

The figure shows a space-filling model of the DNA double helix. It was taken from J. D. Watson's Molecular Biology of the Gene (Third Ed.) (1976). Menlo Park, CA: W. A. Benjamin, Inc., p. 209.

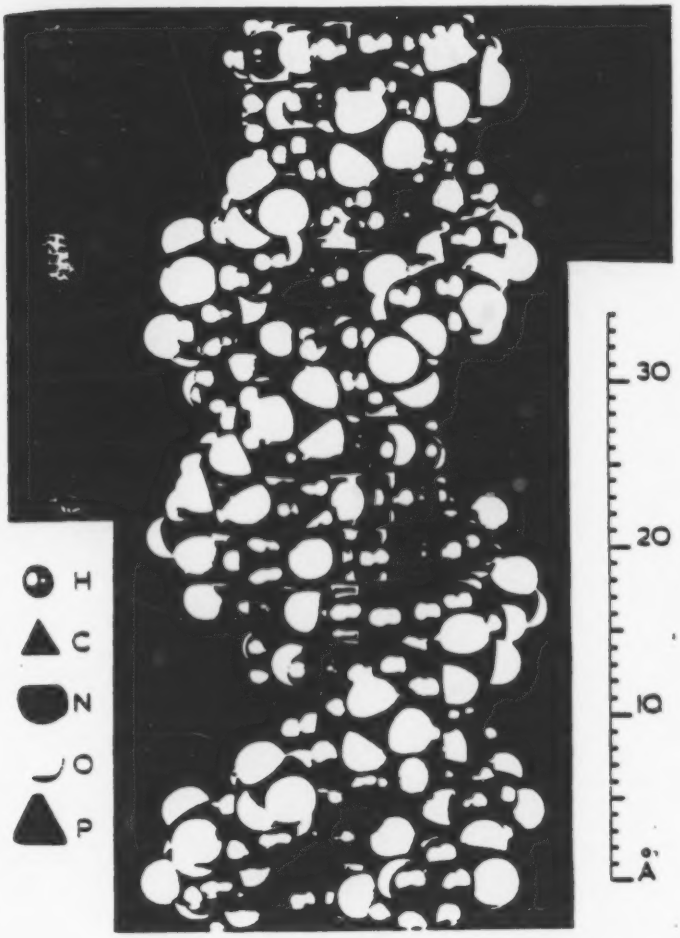

Figure 9–4
A space-filling model of double-helical DNA. The size of the circles reflects the van der Waals radii of the different atoms. [Courtesy of M. H. F. Wilkins.]

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Figure 3

This figure shows a diagram of the processes of DNA replication. It was taken from Watson's Molecular Biology of the Gene (Third Ed.) (1976). Menlo Park, CA: W. A. Benjamin, Inc., p. 212.

The replication of DNA.

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Change

We live in a changing world. Change and the absence of change are important features of both scientific and nonscientific processes. Change can occur in simple, predictable ways: winter gradually gives way to spring, water evaporates from puddles after the rain ends, the sun rises and sets, we (well, most of us, anyway) change from a state of sleep at night to being awake in the daytime. It can also occur in more complicated and unpredictable ways: hemlines rise and fall apparently randomly, the stock market gyrates, mutations resulting in changed organisms occur, the weather changes. It can also fail to occur: a bottle of root beer in the pantry, when opened, contains the same amount of liquid that it had months earlier at the bottling plant; healthy people maintain roughly the same body temperature at all times (with small,cyclic, daily variations); a rock formation photographed a year ago has the same contours now as it did then. In this concept paper, we will explore the concept of change and the related concept of equilibrium .

There are four general patterns of change. They include:

1. Steady changes: those that occur at a characteristic rate.
2. Cyclic changes: those changes that repeat in cycles.
3. Random changes: those changes that occur irregularly, unpredictably, and in a way that is mathematically random.
4. Chaotic change: change that appears random and irregular on the surface, but is in fact predictable (in principle).

Examples of each type of change will now be discussed in detail.

The first type of change is steady change. Change of this sort occurs at a predictable rate. For example, radioactive decay follows a predictable exponential curve. The number of undecayed atoms remaining after a given time in a radioactive sample can be simply calculated if one knows the half-life of the element involved. For example, half of the ^{32}P atoms in any sample will decay in 14.3 days. Similarly, the distance travelled by a car travelling at 55 miles an hour can be simply calculated for any time after the car leaves (assuming it hasn't run out of gas.) Another familiar nonscientific example of steady change would be the steady growth of the balance in an untouched savings account: the rules of compound interest acting on the original balance produce a predictable growth in the daily balance of the account.

The second type of change, cyclic change, is frequently found in nature. A partial list of scientifically interesting cycles would include the phases of the moon, the sunspot cycle, the tides, daily cyclic changes in the levels of hormones in the human body, the sleep-wake cycle in animals, and so on. Some of these examples are familiar to nonscientists as well: we all expect the sun to rise in the east and set in the west once a day, and monthly variations in hormone levels have manifestations that are familiar to almost every female human being over the age of about thirteen. Other familiar cycles include the credit card billing cycle and the annual recurrence of such things as Christmas, Easter, and fund drives on public television.

The third type of change, random change, is also common in nature. Scientific examples would include the occurrence of spontaneous mutations in genes and the radioactive decay of individual atoms. Nobody can predict when a particular gene in a particular organism will undergo mutation, and nobody can tell by looking at a radioactive atom when it will decay. Interestingly enough, though, these processes that are random at the level of the individual gene or atom have definable rates when one looks at all of the genes in a population of animals (the mutation rate) or all of the radioactive atoms in a sample (the half-life). A similar, nonscience, example would be winning the lottery. Winning the lottery is a random event. Beforehand, nobody can predict who will do it; yet the odds of winning are predictable. Again, this is a process which is unpredictable at the individual level but totally predictable at the level of a population of individuals.

One of the most exciting developments in science in the 1980's was the understanding of chaotic change. Chaos occurs when a system obeys completely predictable behavior (i.e. given the exact state of a system at one time, one can determine its exact state at a future time), but our intrinsic lack of knowledge of its initial state causes its future behavior to appear random. Consider the motion of an asteroid, for example. If you knew the exact position and velocity of an asteroid, you could determine its exact position and velocity at any time in the future. However, a small uncertainty (such as a one millimeter uncertainty in its position) will eventually lead to a huge uncertainty in the future. The position of the asteroid in the future will not be determinable, i.e. it will appear random. Similarly, if the location of all of the atoms of our atmosphere were perfectly known at one particular time, the weather could be predicted far into the future. The fact that we don't know those locations exactly (a butterfly flapping its wings in China will disturb some of the atoms, for example) will lead to huge uncertainties in weather prediction; thus we will likely never be able to predict the weather very far in advance. It might seem that it is difficult to differentiate between random change and chaotic change, but there are very precise mathematical relations followed by chaotic systems. One of the main realizations of the 1980's was that many systems previously thought to be random, such as water turbulence, weather phenomena, even cardiac ventricular fibrillation, are in fact chaotic. A good nonscientific example of a chaotic process is the stock market's behavior.

Some systems, finally, are characterized not by change but by lack of change. These systems are said to be in equilibrium. The unopened bottle of soda on the shelf in the pantry illustrates this concept in several ways. First, it is static, at rest. All of the outside forces acting on it are balanced: gravity pulling downward on it is balanced by the force that the shelf exerts to hold it up. Second, the amount of water in it is the same as the amount of water placed in in at the bottling plant. The water in the root beer is not static, however, but is in a state of dynamic equilibrium between two phases: water vapor in the little air space in the neck of the bottle and liquid water in the soda below. The important thing that allows this system to remain in equilibrium is that the bottle is closed. When it is closed, the average number of water molecules that evaporate and leave the liquid phase is exactly balanced by the average number of water molecules condensing from the vapor phase into the liquid phase. Once the bottle is opened, this equilibrium vanishes: water molecules in the vapor phase can and do escape out the neck of the bottle and the water in the bottle will eventually evaporate. In dynamic equilibrium, therefore, a seeming lack of change reflects balanced processes of change occurring within a system.

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The state of dynamic equilibrium that exists in a closed root beer bottle does not depend on any outside forces for its maintenance. Other examples of lack of change, though, represent the interposition of regulatory forces on the system. A simple example of such a system is the thermostat-house system. When the temperature in the house drops below a predetermined level, the sensor in the thermostat notices this and causes the furnace to heat the house. Once the house is warm again, the sensor in the thermostat causes the furnace to shut off. The maintenance of a constant temperature in the house is thus dependent on the regulatory behavior of the sensor. Feedback from the sensor keeps the system stable.

Another, more complicated example of regulated constancy is homeostasis: the maintenance of physical stability within an organism. In humans, for example, everything from our body temperature to the concentrations of different ions in our bloodstream remains fairly constant. This reflects tight control exerted by the cells of our body over these systems: regulation which requires constant sensing of the current state of affairs and compensation for changes that ocur as we move, eat, sleep, and do all of the other things that humans do. One example of the mechanisms involved in homeostasis is the action of insulin and its function in regulating blood sugar levels. As a carbohydrate-rich meal begins to be absorbed by the body, the amount of glucose in the bloodstream begins to rise. In response to this, insulin is secreted by the pancreas into the bloodstream. Insulin stimulates the liver to take up extra sugar and store it in the form of glycogen (a starch-like substance); it increases the uptake of sugar by muscle cells and its conversion into glycogen; it inhibits the liver from producing glucose from its glycogen stores; and it stimulates muscle and liver cells to "burn" glucose for energy at a more rapid rate. These activities reduce the amount of glucose in the bloodstream, insulin secretion by the pancreas drops, and things are back to normal. The control of blood sugar levels by the body is thus complicated and requires a great deal of coordination among the different cells of the body.

Rationale for Teaching the Concept

Change is an inescapable feature of both scientific and nonscientific systems; indeed, it is often the most interesting feature of either kind of system. In science, for example, the study of developmental biology is concerned entirely with the mechanisms behind the amazing changes that occur as an organism develops from seed or fertilized egg into its mature form; meteorology concerns itself with atmospheric changes; much of geology involves the study of the changes that have occurred since the Earth was formed. Outside of science, the daily changes in the stock market are important to millions of investors; changes in the weather matter to essentially everyone; and the changes that occur as a baby grows into an adult fascinate parents, grandparents, and teachers alike. An understanding of the basic types of change, as well as of the concept of equilibrium, is thus useful for anyone.

Suggested Applications

Many areas of science involve change. Below is a very partial list of suggestions for areas that could be used in illustrating change, equilibrium, and regulation.

Steady Change

Simple physical changes:

•Temperature change in water as it is heated (and what do you see at the freezing and boiling points?)
•Titration of an acid with a base; watch the pH change
•Rates of random change (mutation formation, radioactive decay)

Cyclic Change

•Astronomical phenomena (phases of the moon, seasons, changes in day length over the course of the year, behavior of the tides)
•Biological cycles: life cycles, sleep/wake cycle, opening and closing of flowers in plants over the course of the day, the turning of sunflowers to follow the sun, the menstrual cycle

Random Change

•Radioactive decay
•Spontaneous mutation formation in microbes and man
•Study of probability and statistics

Chaotic Change

As discussed above, chaotic change is change that could in principle be predicted, but in fact is unpredictable because of the large numbers of variables involved and uncertainty in measuring starting conditions. Younger children probably have enough difficulty learning that change can be predicted (steady change, cyclic change, rates of random change); introducing chaos at the same time might be confusing. For older children (grades 6-8 or so), the best introduction to chaos would probably be to play with a calculator or computer in the ways suggested in the Glieck book: once they have seen the concept in this abstract way, they'll be able to see it in more concrete ways (one of the few cases where hands-on experimentation may NOT be the best way to introduce a new concept!)

Feedback, Control, and Regulation

•Electronics: study systems like thermostats
•Physiology (human and animal)

Systems

A system is a collection of things and processes that interact with each other and together constitute a meaningful whole. Examples from the realm of science include atoms, chemical reaction systems, individual cells, organs, organ systems, organisms, ecosystems, solar systems, and galaxies; nonscience examples include sewer systems, political systems, the banking system, transportation systems, and so on. All systems share certain properties. These include:

1. Systems have identifiable elements.
2. Systems have definable boundaries.
3. Most systems receive input in the form of material or information from outside their boundaries and generate output to the world outside their boundaries.
4. The interactions of a system's elements with each other and their response to input from outside the system combine to determine the overall nature and behavior of the system.

Systems are made up of identifiable elements and processes. The elements comprising an ecosystem, for example, include all of the organisms present as well as all of the physical features of the area that the ecosystem occupies. The elements of a forest ecosystem would include the different trees, bushes, and smaller plants; the insects, birds, and other animals present; the nature of the terrain; the quality of the soil; the availability of water; the weather; and so on. Defining the elements of an ecosystem thoroughly is a large task. Similarly, the elements of nonscience systems are clearly definable. A school system would include all of the physical property appertaining to the schools and their administration: schools, playgrounds, buses, administration buildings, and so on. It also includes all of the teachers, pupils, administrators, and (ideally) parents.

The boundaries of systems must also be defined. The boundaries of an ecosystem are defined physically: they are the boundaries of the territory that it occcupies. Thus, the boundary of a forest ecosystem is the edge of the forest. An ecosystem's boundaries can be drawn somewhat arbitrarily; one can speak of a backyard ecosystem or of the planetary ecosystem. The first ecosystem would thus be an element of the second ecosystem. The approprate choice of boundaries for an ecosystem depends on the phenomena that one wishes to study: to study global warming, it is necessary to include the whole planet, but a study of the effects of man on the alpine tundra could involve only a single mountaintop. Similarly, the boundaries of nonscience systems can be defined in somewhat arbitrary ways, depending on the nature of the process under study. The boundaries of a school system could be chosen to exclude neighboring systems and the Federal Government: although all of these elements can affect the school system, they are not really integral to its behavior.

Drawing the boundaries of a system appropriately can reveal much about its nature and behavior. Including phenomena and elements that are irrelevant to the properties under study will make understanding the system unnecessarily difficult. Including detailed consideration of the daily actions of members of the Williamsburg City Council in a study of the overall behavior of the American political system adds variables that are probably insignificant for the behavior of the system as a whole and therefore makes the study of the system unnecessarily difficult. Excluding the press from the system, however, probably decreases the understanding of the system, even though the press is not a formally defined branch of government. Although the press could be considered as an external actor that produces

input into the system, in practice the actions of the press are so tightly intermeshed with the actions of those that run the government that excluding the press from the government system would make understanding the system more difficult rather than less.

As discussed in Science For All Americans, one of the best examples of the importance of properly defining the boundaries and elements of an experimental system is Louis Pasteur's elegant experimental solution for the problem of the spontaneous generation of living organisms. Before the nineteenth century, it was widely believed that living organisms arose spontaneously from nonliving matter, without benefit of the action of other living things. Rats and mice were thought to arise spontaneously from old rags; maggots from old meat. In the 1800s, Louis Pasteur approached this problem experimentally and resolved it. He showed that if flies were kept from contact with meat, no maggots subsequently arose from it; and if meat broth was boiled and then kept in sealed flasks or in flasks that allowed the entry of air but not of dust particles, then the broth did not spoil. By drawing the boundaries of his experimental system to exclude certain elements (namely flies and bacteria), Pasteur proved that meat alone was insufficient to generate maggots and meat broth alone did not spoil. Thus, the doctrine of spontaneous generation was laid to rest.

Another example of the importance of correctly understanding of the boundaries and elements integral to a system comes from the controversy over the origin of life on Earth. The science of thermodynamics has been used (inappropriately) to argue that life could not have evolved from nonliving chemicals through simple life forms and up to the many complex forms that we see today; this argument is based on a misunderstanding of the boundaries of the system in which life evolved and an incomplete understanding of thermodynamics. Thermodynamics is the science that sets the limits on the energy efficiency and possible outcome of physical and chemical processes. The three laws of thermodynamics can be summarized as follows:

1. Energy can neither be created nor destroyed, only transferred or changed from one form to another.
2. In an irreversible process, the entropy (degree of disorder) of the universe increases; only in a reversible process will it stay constant. The entropy of the universe cannot decrease.
3. At the temperature absolute zero, the entropy of perfect crystals and compounds is zero.

The second law of thermodynamics has been misused to argue that life could not possibly have evolved, because over time the complexity of living things has increased, and hence the system of life on Earth has become more ordered, not more disordered. The basic flaw in this argument is that its proponents have neglected to include the sun in their calculations. Solar energy is the source of most of the energy used by organisms; thus the thermodynamic properties of the sun must be included in the system. The net entropy of the sun has increased by a degree that is orders of magnitude greater than the degree of entropy decrease caused by the origin and actions of all life on Earth; thus, the entropy of the universe has increased, as it theoretically should.

A third fundamental property of systems is that they can receive input from and act on the world outside their boundaries. Input into a school system, for example, includes Federal financial and material assistance. Output from a school system includes educated students. Input into an ecosystem includes such things as solar energy; output from an ecosystem includes such things as carbon dioxide released

into the atmosphere as a result of animal respiration and oxygen released by plants.

The final fundamental property of a system is that its overall behavior depends on the properties and interactions of its parts. For example, understanding the behavior of an ecosystem (for example, whether it is stable or likely to change, whether it is delicate and sensitive to the incursions of man or whether it can survive human influence with few changes) depends upon understanding the roles of the different elements in the ecosystem and their interactions. Thus, prediction of the number of deer that can be safely hunted in a given area depends upon knowing how fast they reproduce, which wild predators are present and what percentage of the deer population they kill, whether disease is present in the deer population and likely to reduce numbers substantially, which plants the deer use for food and how many deer the plant population can support without being reduced too far to replace itself, and so on.

This dependence of the behavior of the whole system on the properties and interactions of its parts is also seen in nonscience systems. The behavior of the Federal Government depends on the actions and motivations of its members, their interactions with each other, and their reactions to input from their constituents and from the outside world. The behavior of the local sewer system depends on the amount of material it receives, the age of the pipes, the capacity of the treatment plant, and so on. Attempting to understand the behavior of the whole system based on the nature of its parts is the essence of the philosophy of reductionism, which has been a highly successful approach to the study of systems in general.

Rationale for Teaching the Concept

The understanding of the behavior of one system will help understanding of other systems. Defining the elements, boundaries,. inputs and outputs of a system helps to understand its behavior as a whole. Once a child has learned to do this for a simple system, he will be able to apply the process to other, more complex systems. This will help him understand the scientific process, as setting up successful experiments involves determining which elements should be included and paying close attention to the inputs and outputs of the system; varying the elements present in the experimental system may well change the experimental outcome in ways that illuminate the functioning of the system. More generally, the study of certain scientific systems will deepen a child's understanding of the world around him. Every child should have some understanding of the ecosystem of which he is an element and the solar system in which he resides.

Suggested Applications

There are two different ways to approach the concept of systems with children. The first involves weaving it into the experimental work that they do in the course of their science studies. Defining the experimental system thoroughly and paying attention to the essential variables in the system and excluding the others from consideration are activities critical to any lab science course. The second approach to the concept involves teaching them about some basic scientific systems. Many scientific systems are accessible to children, at least at a simple level. These include systems from many disciplines, including chemistry, geology, biology, and astronomy, as listed (albeit in incomplete fashion) following:

Biology
ecosystems
organ systems
organisms: physiology, behavior

Chemistry
chemical reaction systems

Geology
The planet Earth as a geological system: plate tectonics and its manifestations
Geologic change in mountain ranges, river systems, and the like

Meteorology
Weather systems

Astronomy
Solar systems
Galaxies
Earth-moon system

Problem-Based Learning

The following is an example of a problem-based learning situation that could be used to illustrate the system concept.

The problem: You own a gardening store. Several townspeople have signed a petition asking you to stop selling some of your products. What should you do?

Areas for students to explore:

1. The garden as a system: look at the interactions of the plants and animals present and seek to minimize animal and disease destruction of the plants.
2. Organic farming techniques
3. Resistant plant varieties
4. Plant varieties that are suitable for the local area's soil conditions, sun-shade conditions, and weather patterns.

Activities for students :

Plant and tend two gardens: an organic garden and a garden in which chemical fertilizers, insecticides, and herbicides are used. Record the amount and kinds of work needed to maintain each; the amounts of chemicals used in the chemical garden; and the yields of the different fruits, vegetables, and flowers planted in each. Report results.

D(BS)

Evolution

Evolution is both one of the most fundamental scientific concepts and, specifically in its application to biology, one of the most controversial for the lay public. The ideas of Charles Darwin and Alfred Russell Wallace and those who came after them caused a great revolution in the way in which biologists approach the fundamental problems of their discipline; they caused an even greater revolution in the Western view of man's relation to the universe. Although Darwin's ideas are nearly 150 years old, their broad implications are still controversial for many people in this country. As will be discussed later, the sheer power of the evolutionary concept has created problems in its teaching.

Evolutionary processes can be found in many places besides biology, however. Stellar evolution, geologic change, and even such nonscience phenomena as the changes of usage and orthography in a language over time all display characteristics of evolutionary processes. These characteristics include:

1. Change occurs with time.

2 For each different evolutionary process, there are identifiable rules that govern the process of change. The precise rules for a given process depend upon the fundamental nature of the evolving system, but the rules for one evolutionary process are often similar to those for other, unrelated processes, as will be discussed below.

3. The form that the present takes depends directly on the possibilities inherent in the form of the past; some types of change are more likely than others. In addition, the nature of the past can sometimes be discerned from the nature of the present.

In biological evolution, the best illustration of the occurrence of change over time can be found in the fossil record. The oldest fossils on the planet are approximately three billion years old, and are detectable only upon microscopic examination. These are fossilized organisms that resemble modern-day bacteria, some of the least complex life forms known. In younger and younger rocks, paleontologists find progressively more complex forms of life. The fossil record clearly shows the progressive appearance (and, in many cases, eventual disappearance) of a huge variety of life forms. Based on the fossil record alone, phylogenetic trees that show the relationships between ancestral forms and their descendants have been constructed, and the clear relatedness of all life forms has been demonstrated. Other, independent, evidence exists for the relationships derived from study of the fossil record. Using the techniques of molecular biology, geneticists have calculated the evolutionary distance between modern-day species based on the degree of similarity of their DNA sequences. These relationships agree precisely with the evolutionary relationships derived from study of the fossil record. Organisms clearly changed with time.

The occurrence of change over time is also plain in many other systems. Change processes of interest to geologists include the building up and weathering down of mountain ranges; the carving of valleys by rivers and glaciers; the gradual deposition of sediments and their eventual transformation into rock layers; the earthquakes, volcanic activity, and slow movements of the continents that arise from the movements of the plates that make up the Earth's crust; and the collection of processes that formed the Earth and the Moon. Processes involving change over time that interest astronomers and physicists

include those dating back to the origin of the universe itself: the Big Bang, galaxy formation, stellar evolution, and so on.

Change over time is also apparent in other, nonscience, areas. One area in which the study of change over time is the most meaningful is the study of languages. The English language that Chaucer used has changed appreciably since his time, both in spelling and in usage. Indeed, Chaucer in the original is difficult for the average English-speaking person to understand.

The large changes that have occurred in English since Chaucer's time serve to illustrate another generalization about evolutionary processes: each has a characteristic timescale. Stellar evolution, the collection of processes that take a star from its birth to its death, occurs over billions of years. Our sun, for example, is middle-aged: five billion years old, it has about another five billion years to go before it burns out. Major geologic changes, such as the raising of mountain ranges, take place on a shorter timescale than does stellar evolution, tens or hundreds of millions rather than billions of years. The evolution of modern humans from our nearest nonhuman ancestors took less than twenty million years, and all of the species that evolved after the dinosaurs did so in the last 65 million years: the long end of the biological timescale is comparable to the short end of the geological timescale. All of the changes in the English language have occurred, in contrast, in less than the 5000 year lifespan of a bristlecone pine.

Every evolutionary process occurs according to identifiable rules. Biological evolution, for example, is driven by three major processes: genetic mutation , natural selection, and genetic drift. In order for a new variety of an organism to arise within a population, the germline DNA (the DNA in cells that will go on to form a new individual, such as sperm or egg cell DNA) of an individual organism must undergo a chemical change that results in a new attribute for the organism's progeny. For example, a white coat color for a mouse can arise as a result of a mutation that inactivates one of the genes that controls melanin production; hairs in the mutant animal will lack melanin pigment and be white rather than colored. The process of mutation is random: any gene can undergo mutation at any time. Some germline DNA mutations are deleterious: they lead to reduced or inappropriate function of the gene that they affect. Other germline DNA mutations are considered to be neutral, not likely to affect the function of the gene in which they reside. Still others are potentially advantageous for the organism that bears them. These mutations are the raw material for the processes of natural selection and genetic drift.

The premise of natural selection is that organisms which bear advantageous characteristics will be more likely to leave more descendants than organisms of the same species lacking these characteristics. With time, therefore, an advantageous mutation's frequency within the population will grow and the overall nature of the species (as defined by the characteristics observable in most of its members) will change. Mutations spreading through isolated subpopulations can result in the formation of new biological species, distinct from the parental species.

Mutations can also spread through a population by the processes of genetic drift. These random processes can result in the increase in frequency of deleterious mutations as well as neutral and advantageous ones. For example, if the number of animals in a population is drastically reduced, the amount of genetic diversity in the population will also decline: if the only two animals in a population bearing a particular advantageous mutation are killed by a rockslide , the mutation will be lost to the population's descendants. Cheetahs went through such a population bottleneck during their evolution.

D(BS)

Genetic studies have shown that randomly chosen cheetahs are much more genetically similar to each other than, say, randomly chosen lions. This has been bad for the cheetah species as a whole: cheetahs bear fewer viable offspring than do other closely related species because they are so inbred. Genetic drift can thus have selectively disadvantageous results.

Like biological evolution, the evolution of a language also occurs by identifiable processes, some of which are reminiscent of the processes by which biological evolution proceeds. In a process that is the language equivalent of mutation, new words enter a language in a number of ways, including the invention of new words to describe new ideas (for example, spacecraft, telephone) and the borrowing of words from other languages to illustrate concepts previously foreign to speakers of the language (glasnost, mullah.) Old words fall out of a language through disuse (the equivalent of deleterious mutations being selected against or of genetic drift). Furthermore, the usage of a word can change through time . Orthography also changes, either through government-mandated reforms such as those made by the Bolshevik government after the 1917 Russian revolution, through the standardization of spelling by the writers of dictionaries (for example, Noah Webster), or simply through changes in the way the general population misuses a word (the substitution of Xmas for Christmas, for example.) Pronunciation can also undergo rapid change, as illustrated by the formation of large numbers of dialects of English during the time in which the British Empire rose and fell. The factors that influence dialect formation (geographic isolation, essentially random changes in usage, the introduction of new words to describe new conditions) are very similar to those involved in the formation of new species through the processes of mutation, natural selection, and genetic drift. Indeed, understanding biological evolution can enrich the understanding of language evolution: evolutionary trees showing the degree of relatedness of different languages can be drawn with the same algorithms used to demonstrate the evolutionary relationships between different species. A particularly interesting example of the use of such trees can be found in the article " Genes, Peoples, and Languages" by Luigi Luca Cavalli-Sforza (*Scientific American* 265, 104 (1991.)) The author and his coworkers compare genetically derived family trees for different human populations with the trees that relate their languages. Together with the archaeological record, the different types of phylogenetic trees can be used to support the hypothesis that humans originated in Africa.

The final characteristic of evolutionary processes, that the form of the present depends upon the form of the past, can be illustrated with an example from biological evolution. In biology, there are limits to the new kinds of organisms that can be formed from existing organisms. Humans with green blood (based on copper a la Mr. Spock) are extremely unlikely to arise by natural processes from present-day humans: the number of mutations that would be required would be too great and the likelihood is that the intermediate forms would possess mutations that were highly inimical to survival. Other changes, though, are both possible and likely. Genes specifying the presence of five digits on every appendage are present in essentially all mammals, as can be shown by the analysis of structures as disparate as the human hand, the paw of the cat, and the flipper of the whale. The way in which these genes are regulated and the genes which operate in addition to these genes differ in each organism, however, and produce the different structures that we see. The presence of five digits per limb reflects the common evolutionary heritage of mammals; the different ways in which these genes are used reflects the broad evolutionary possibilities for use of similar structures. Biological evolution is thus constrained to use the available materials in a variety of ways to produce a variety of new organisms; new varieties do not arise entirely de novo. There is a limit to what new mutation alone can accomplish. This characteristic constraint of possibilities is shared by all other evolutionary processes. For example, stars below a

certain size can only burn themselves out rather than die with the bang of a supernova: the mass of a star thus constrains its possible final fate.

All other evolutionary processes also share the characteristic that their history can be brought to light by a careful analysis of the form of the present. For example, essentially all organisms on Earth share a common genetic code: the genes of bacteria can be translated into protein in the same way that the genes from mammals can. Thus, all life on earth had to have had a common ancestor: the odds that the same basic genetic coding process arose twice are vanishingly small. This conclusion becomes even stronger when the other biochemical commonalities between different organisms are taken into account. The form of present-day organisms thus tells us a great deal about the history of the evolutionary process.

Similarly, the evolution of the Russian language can be illuminated by analysis of the origins of modern Russian words and study of the times in which they came into use. Many words referring to nautical matters came from Dutch, reflecting Peter the Great's trip to Holland and his subsequent import of Dutch shipbuilders and sea captains to construct his fleet and train his navy. Many scientific words came directly from German: science was not a subject native to Russia, but it was a subject in which the Germans excelled. Other Russian words reflect the sad history of invasions by the Tatars and other conquering armies. Religious words (as well as the Cyrillic alphabet) reflect the Christianization of Kievan Rus by Byzantine monks. Much of the history of Russia can thus be found in the Russian language.

The comparison of the processes of biological evolution and language evolution illustrates the commonalities in these two different systems. Although the timescales are vastly different, both processes involve change over time, both proceed according to identifiable rules (which share a number of similarities), and the products of both processes display evidence of their evolutionary history. An understanding of the evolutionary process in one system can therefore enrich an understanding of other evolutionary processes and, thus, an understanding of the world as a whole.

A special plea should be made on behalf of the study of biological evolution. This is one of the two or three most fundamental concepts in all of biology; it is impossible to understand modern biology without it. An appreciation of evolutionary pressures is important for understanding ourselves, because we, like all animals, evolved, and were subject to the same stringent evolutionary demands as all other organisms: compete, reproduce, protect your offspring until they mature, ensure the success of your tribe. These pressures are still evident today: overpopulation, war, and perhaps even teenage pregnancy can be seen as results of these pressures. Biological evolution thus has strong and highly controversial implications for society.

Rationale for Teaching the Concept

Evolution is a concept that can be translated down to even the youngest student. This will be illustrated with examples for biological evolution; it is important to remember, though, that such areas as astronomy and geology are also translatable to children. Preschoolers who love dinosaurs know that the animals present on Earth now are not the same as those that were around several hundred million years ago. Children in the primary grades can appreciate the evolutionary adaptations of desert plants for a desert

environment and decide why swamp plants probably wouldn't make it in the desert. Older children can look at the chemistry of fossil formation and find fossil evidence for earlier types of organisms. Middle school children can begin to weigh the merits of the competing hypotheses regarding the way in which the great extinction event at the Cretaceous/ Tertiary boundary may have occurred and relate their understanding of that event to the possibilities posed by the nuclear winter hypothesis. The study of evolutionary processes can easily be accomplished in the field and at the lab bench or computer terminal: thus the potential for hands-on science is great. For all of these reasons, as well as those enumerated above, the broad concept of evolution is eminently suited to study by high ability children.

Selected Applications

Evolution can be presented in progressively more detail and at higher levels of abstraction as children grow. The youngest learners will profit most from observation of the world around them and of the variety of objects in nature. In order to understand that the natural world can change (and has changed) in major ways, they need to know their small corner of the world well and to observe the small changes that take place in it all of the time. Older children can begin to appreciate the processes responsible for the current shape of the world around them and see evidence for the past and present action of those processes. The oldest learners should be able to handle the more abstract science behind the phenomena that the younger learners are observing. The following is a list of suggested topics.

Suggested topics for study:

1. Grades K-2: The world is a complex place with great variety.

    a. local biological variety
    b. local geology
    c. simple observational astronomy and the Copernican theory

2. Grades 3-5: The elements of the natural world interact with each other in identifiable ways and change through identifiable processes.

    a. Biology: introduce the concepts of ecosystem, adaptation, niche; work out how humans impact other organisms in the local ecosystem; compare the organisms in different ecosystems (forest vs. desert, for example).
    b. Geology: processes of geological change: weathering, rock formation and breakdown; processes that shape the landscape and evidence for their action in the local landscape.
    c. Astronomy: use a telescope to look at nebulae and other interesting objects.

3. Grades 6-8: Begin to look at the history of evolutionary changes on the earth and the abstract science of evolution.

    a. Biology:

        (1) Genetics: study simple Mendelian genetics and understand the concepts of gene, gene frequency, and mutation.

(2) Natural selection: define explicitly and look at some examples (industrial melanism in English moths, for example).

(3) Human evolution: look at the fossil record; the genetic and behavioral commonalities between us and our nearest ancestors; the ways that humans are still subject to natural selection and the cultural methods that we have developed to evade the selective forces that shaped us.

b. Geology:

(1) Plate tectonics: evidence, theory, predictions

(2) Geological hazards: why don't you build a house on the sand?

c. Astronomy:

(1) Planetary science; pictures of other planets show evidence for the same sorts of landscape-shaping processes as occur on Earth; similarities and differences between other planets and Earth.

(2) Stellar evolution; evolution of the universe as we know it today.

Reductionism: Structure, Function, and Pattern

Why do scientists break things apart in order to study them? They are trying to understand the structures and functions of the component parts of the thing they are studying. Such an understanding will, in turn, help them to better understand the properties of the whole. This strategy is known as reductionism.

Reductionism has been highly successful in science. Biologists use dissection, microscopy, and biochemical techniques to determine the structures and functions of the parts of biological systems; geologists look at crystal structure, mineral composition, and the arrangement of rock layers in core samples to better understand the geology of an area of interest; physicists use huge particle accelerators to smash elementary particles together in order to study the nature of the universe (something like smashing Swiss watches together to see how they work.) Such studies have revealed the structure and function of DNA, the structure of the Earth, and the nature of the fundamental particles that make up all of matter.

The strategy of reductionism is also useful in areas outside scientific research. Students of auto mechanics study the structure and function of the parts of an engine in order to understand how an engine works and what to fix when an engine comes in with a particular sort of problem. The medical art of diagnosis depends on the diagnostician's understanding of the functions of the different parts of the body and of the symptoms that indicate that a particular part of the body is functioning abnormally, either in response to an infection or for some other reason. Reductionism is even applied by children: they instinctively know that taking things apart will help them to understand the thing better, whether the thing is a set of nesting cups or their father's stereo.

There are many examples of the utility of a reductionist approach to a scientific problem. Our understanding of biology, for example, is heavily dependent on reductionist studies of the structures and functions of the parts of cells. The study of cellular structure began in the seventeenth century, when the English microscopist Robert Hooke coined the term cell in his description of the microscopic structure of cork. As light microscopes improved, more and more became known about the internal structure of cells. Selective stains revealed that different parts of cells had to be chemically different from each other because they took up chemically different stains; the staining patterns in different cell types also suggested that different parts of cells had distinct specialied functions. The nucleus of the cell was described, and by the beginning of the twentieth century, the interesting behavior of chromosomes during cell division had been noticed and correlated with the ideas of Mendel about the behavior of genes.

Understanding of the nature of cells deepened beginning in the 1940s and 1950s. Using the newly invented electron microscope, Keith Porter and his colleagues at the Rockefeller Institute pioneered the study of cellular structure with the electron microscope. Once the structures had been described, clues to their functions were found in their arrangements in different cell types that performed different sorts of activities; their functions were then identified by experiments involving such techniques as physical fractionation and chemical staining. The rough endoplasmic reticulum, for example, is prominent in cells making proteins for export (liver cells and the cells in the pancreas that make digestive enzymes, for example.) From cell fractionation and staining experiments, it soon became apparent that this part of the cell is the location of secreted as well as membrane protein synthesis. Thus, if a new cell type of

unknown function is found to have a lot of RER, the immediate response of the cell biologist is to find out what sorts of proteins the cell produces for export.

Another famous example of the importance of structure-function studies comes from the domain of physics. In the early 1900s, Ernest Rutherford was working on the problem of the structure of the atom. Many different possibilities existed, but there were no firm data to distinguish between them. Rutherford shot positively charged alpha particles (now known to be helium nuclei) at a target made of very thin gold foil. Most of the alpha particles passed through the foil undeflected, but a small portion were scattered (bounced back) by as much as 180 degrees. This clearly indicated that most of the gold foil was basically empty space as far as the alpha particles were concerned, but embedded within that empty space were small, massive, positively charged regions. Atoms were known to contain both positively and negatively charged regions, and the negative charge was known to reside on lightweight electrons that would be unable to influence the path of the alpha particles through the foil. The results of the experiment therefore indicated that atoms had a small, massive, positively charged nucleus, while the electrons had to be somehow responsible for the rest of the apparent size of the atom. Rutherford's experiment was thus the first indication of the structure of the atom that is now accepted today: a small, positively charged nucleus surrounded by a cloud of electrons. Further refinements of the atomic model proposed by Rutherford have resulted in our current understanding of atomic and molecular structure. Much of our understanding of chemistry flows directly from these models.

A nonscience example of the utility of reductionism is the study of language. The study of the parts of a language helps us to understand statements in that language. Russian, for example, is an inflected language. The endings of words change depending on the role of the word in a sentence. The changes in the endings of the words follow predictable patterns, so (for the most part) one can easily determine the part of speech and the role in the sentence (subject, object, verb, or whatever) of an unknown word . The adjectives that modify a noun all have endings that agree with the ending of the noun; verbs have different endings from those of nouns and adjectives, and the endings of verbs tell the informed reader who or what is performing the action. The parts of the words are themselves informative. If one has learned the 650 or so common roots of Russian words, one can often break an unknown word up into its roots and take an educated guess at its meaning. For example, if a word with an adjectival ending contains the root "gloop" (stupid), it is probably a safe guess that the person described by this adjective may not be particularly smart. A good understanding of the different parts of the Russian language, including the grammatical rules, the endings of the different parts of speech and their conjugations and declensions, and the roots of the language, therefore enhances the understanding of the language as a whole.

An interesting feature of reductionist studies of structure and function is that they often reveal an underlying order or pattern that helps to explain the behavior of the phenomenon or object under analysis. The grammar of a language is such a pattern, as are the rules governing atomic structure. The arrangement of atoms in a crystal is a physical example of such a pattern. Graphite (the form of pure carbon used as pencil lead), for example, consists of parallel flat sheets of covalently bonded carbon atoms. The sheets adhere to each other through much weaker van der Waals interactions. Diamond, the other familiar form of pure carbon, has a very different crystal structure. Each carbon atom in diamond is covalently bonded to four other carbon atoms whose nuclei are located tetrahedrally around it. The weak point of the graphite crystal lattice is the van der Waals bonding between parallel sheets: slippage

along these sheets occurs quite easily and gives graphite its characteristic ability to rub off on another surface. The diamond crystal lattice has no such weak points, giving diamond its characteristic hardness.

Physical patterns, such as crystal structures, often display the property of symmetry. Symmetry can be defined as a regularity about a structure that appears when it is rotated or translated (moved along a straight line.) The crystal structure of graphite has symmetry: movement of the crystal lattice along a line perpendicular to the parallel sheets for a distance exactly equal to the distance between the sheets produces a structure that looks identical to the original structure. Familiar objects also display the property of symmetry. For example, stop signs (if you neglect the words) have eightfold rotational symmetry: if they are rotated about their center through an eighth of a turn, the new arrangement is exactly superimposable on the old arrangement . Similarly, snowflakes have the familiar hexagonal rotational symmetry. Symmetry can also refer to the superimposability of mirror images. A baseball, for example, is superimposable with its mirror image. A hand, in contrast, is not: a left hand's reflection looks like a right hand. The human body displays bilateral symmetry along the axis defined by the spinal cord: a mirror image of the right side of the human body looks like the left side of the human body. Symmetry can be found in many natural objects.

Symmetry is fundamentally a mathematical idea. All of the symmetries discussed above can be described very simply in terms of mathematical operations performed on the coordinates that describe the objects. Similarly, mathematical equations can have symmetries. These symmetries can point to fundamental properties of the things that those equations describe. For example, there are symmetries in the mathematical description of the behavior of the fundamental particles that make up matter. These symmetries are important and useful: they resulted in theoretical predictions of the existence of other fundamental particles that have since been experimentally verified (see the Hawking reference in the bibliography for details.) Thus the underlying symmetries in the equations that describe the fundamental particles that make up all matter resulted in important predictions about the nature of matter: underlying patterns can help scientists understand the behavior of the whole.

Rationale for Teaching the Concept

Reductionism is a useful strategy both inside and outside of science. The ability to look at the parts of a complicated thing and figure out how they have to fit together can be useful for everyday life , as anyone who has ever tried to assemble a tricycle late on Christmas Eve knows. It is a nice way of approaching technological problems as well: explaining how a piece of machinery works is much more interesting than just presenting it as a black box with a known function.

Suggested Applications

The ideas presented in this concept paper can be approached at several levels in a variety of disciplines. Some possibilities include:

For the study of structure-function relationships:

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Biology: Macroscopic:

- •Look at evolutionary structural adaptations; relate them to the creature's lifestyle/ life cycle. This provides students endless possibilities for fieldwork.
- •Look at parts of creatures by dissection: safest to stick with plants, however, as students can be squeamish. There are great films and videos of parts of animals.
- •Microscopic: Observe structures directly.

For illustration of patterns:

Geology: Crystal structure; use for classification, explanation of properties such as hardness; can look at symmetry here.

Meteorology/Physics: Optical effects caused by meteorological phenomena (sundogs, rainbows, rings around the moon); should be accompanied by basic physics on the behavior of light (prisms, lenses, diffraction, etc.) All of these things can be explained either at the simple level of "Oh, look, here's the pattern of light that this makes" or in more complicated mathematical terms for the advanced student.

Mathematics: play with symmetry groups, fractals: computer approaches possible: use Judson's Xerox machine tricks to illustrate; have students make their own designs and look at the possibilities.

Classroom Applications

Biology

The problem of a creature's adaptation to its environment is of perennial fascination for biologists. This could be brought down to a child's level as follows:

1. An ecosystem could be briefly described, and the animals within it listed. Each child could then be asked to pick an animal in the ecosystem and learn as much about it as possible. They should be asked to study the different unique features of the animal and think about how they function in enhancing the animal's function within its niche; they can then present their findings to the class.

2. The children could be told a few facts about an imaginary ecosystem (for example: it's on the planet Xzxzgg which is Earthlike except that it is 25% larger; it has only oceans with interspersed islands rather than large continental areas; the largest omnivore has the size and disposition of a shrew; and so on.) Each child could then design an animal to fit a particular niche in this imaginary ecosystem (for example, amphibian insectivore, largest predator, and so on), paying particular attention to the structural adaptations that matched the animal to its lifestyle. The ecosystem could then be fully described by the class.

Technology

One approach to reductionism that fits into this category could be entitled "Fun at the Army Surplus Store". Many children enjoy taking mechanical things apart. This natural behavior can be used to help them understand such things as the uses of electricity and the different kinds of simple machines

(screws, wheels, levers, and so on).

At the beginning of the exercise, each child could be given a choice of a number of Army surplus junk items: everything from old typewriters and clocks to field phones and other interesting military items (the use of munitions for this exercise, however, is not recommended.) Students would then be given tools and allowed to take each item apart, diagramming the arrangement of the parts as they went and saving them in labeled containers (Ziploc bags would work well) so that there would be at least some hope of putting the things back together again. They would be asked to figure out what the thing did and as much as possible about how it did it; they could then present their results to the class.

Suggested Applications: General Considerations

Some general suggestions that apply to the teaching of essentially all of the concepts in this document follow.

A. Appropriate Use of Laboratory Activities in Science Programs for the Gifted

Student labs, from elementary school through college, can be boring, messy, purposeless affairs. A student walks into lab, reads the instructions, attempts to duplicate the procedure described, writes down numbers or observations in the spaces provided, and then writes a lab report according to the instructor's prescribed format. The problem with this process is that, too often, the student doesn't really understand why the experiment was performed in the first place: why it was important, what it tested, or what the results implied. Instead of being a learning experience, the lab was an exercise in following instructions. The inevitable problems that accompany bench work were sources of frustration not because they hindered the development of understanding but because they made the student have to stay longer in the lab or, even worse, affected his grade on the lab.

Lab work doesn't have to be boring and purposeless. Good laboratory experiences can open up new areas of science for a student, illustrate processes that can only be described inadequately by a textbook, and give a student the fundamentals of experimental design and scientific proof. For these reasons, scientists and science educators want their students to participate in as many good laboratory experiences as possible.

There are many different commercially available curriculum packages that include laboratory work. They range from the standard basal text materials to small, innovative enrichment packages. The types of laboratory experiences that these curriculum packages contain can be sorted into a number of different categories, as described below:

a. Dry labs : labs which mimic scientific processes without using scientifically appropriate materials: examples would include modeling the behavior of meiotic chromosomes with bits of string, making baking soda volcanoes, or comparing gummi worms with nightcrawlers.

b. Labs whose entire purpose is teaching the proper use of equipment: for example, labs entitled "Introduction to the Microscope" or "Metric Measurements. "

c. Recipe labs: examples would include the standard chemistry labs which basically ask "if you add X to Y, what happens?"

d. Observation labs: dissecting a frog, observing the phases of the moon, looking at slides of onion root tips to observe mitotic chromosomes.

e. Question labs: labs which pose a scientific question and address it experimentally

f. Open-ended experiences: Lab experiences which don't allow the student to merely follow a protocol but, rather, require him to design and perform an appropriate experiment to test a

hypothesis that he has made some contribution to developing. Such lab experiences can be part of elaborate critical thinking packages or can be simple one-liners that begin with such words as "Design an experiment..." or "What if?"

Some generalizations can be made about the intrinsic scientific value of labs in these different categories which are listed in ascending order of merit.

Most dry labs are a nonproductive way to use class time. They do not really pose a scientific question; the materials used bear no relation to the actual process; students do not even get to observe something real. If you think that going through the motions would be fun for students or reinforce something that they've learned in the text, have them do these labs at home for extra points.

The scientific value of many learning-to-use-equipment labs may also be minimal. While a several-day lab session devoted to the proper use of the microscope is fully justifiable for middle school students, a full day lab session devoted to teaching them to use a metric ruler is probably not as they could pick up this skill in a question lab experience just as well. The material presented in such labs could be included in a recipe lab, observation lab, question lab, or open-ended lab experience equally well, and presenting it in such a context will probably enhance the students' motivation to learn it.

Recipe labs used in moderation are all right, particularly in such situations as chemistry class where you don't want to have the safety problems that flow from students experimenting on their own: they still get to observe real chemical behavior. In addition, these labs teach students to follow a scientific protocol, which is a valuable scientific skill.

Observation labs are great if students know what they're looking for beforehand. If they're prepared, the observations will enhance their understanding of the phenomenon they're supposed to observe. Some provision should be made to encourage them to note as many features of the system they're observing as possible: new insights about cell structure may hit them while they're only supposed to be looking for mitotic chromosomes in onion root tip cells, for example.

Question labs are potentially very valuable: they offer the student a window into the solution of a scientific problem. There are some excellent curriculum materials available that provide good question lab experiences. Unfortunately, most question labs (particularly those in basal curricula) look like recipe labs: the student is given a list of materials and instructions for her manipulation, but not encouraged to develop the scientific question on her own or to participate in the experimental design phase. As a result, the student frequently does not understand the purpose or design of the experiment that she performs, and the scientific process component of such labs is lost. As the curriculum world is loaded with this sort of question lab, perhaps the best thing to do is to convert canned question labs into more open-ended laboratory experiences. Open-ended experiences necessarily take more time than do canned question labs, because the students have to think about what they're going to do before they do it. If even a few such canned labs are converted into open-ended experiences during a school semester, though, the net effect will be positive. An example of such a conversion is included below.

Open-ended laboratory experiences are the closest approximation to doing real science that a student is likely to have. It is worth omitting unimportant recipe labs, dry labs, and in-class textbook reading

exercises in order to squeeze in the time for these things in class. The standard way of including such experiences has been to make the student do them alone as an outside project or as a science fair project. The problems associated with this approach are the following:

1. It's just as hard for the student to make time for such activities outside class as it is for the teacher to do it in class. Such projects are often left to the last minute and done in a rush: done badly, in other words.

2. The process of doing science goes very slowly in isolation. A student working alone or with another classmate but without much adult input will not get very far and the process will be depressing and frustrating.

3. The competitive aspects of science fairs often force the student to pay more attention to appearance than to substance: the neatness of the poster and its dimensions are often stressed far more than the soundness of the student's experimental design or the originality of his ideas. The unpublishability of negative results or failed experiments should not be an important factor in a student's science experience (which is also why basing a grade on the quality of a chemically synthesized product is a bad idea.)

4. Competition is also a real turn-off for many students (particularly science-prone ones who have learned that it's a lot safer to keep a low profile than to arouse the envy of their classmates, or for girls who think it's socially inappropriate to appear smart.) While real science does have competitive aspects, the reality is that most of a scientist's work occurs in collaboration with other scientists. This is both enjoyable and productive, but it is not an element in most science fair experiences.

In order to integrate open-ended experiences into the classroom in a productive way, it is necessary both to allocate class time for such experiences and to monitor the different stages that the students go through in a careful way.

Example: Uncanning the Experiment

Converting a canned question lab into a more hands- and brains-on process for the student is relatively staightforward, although it demands a bit of preparation. Don't just hand the student the lab worksheet and have him follow it. In fact, never give the student the prepared lab worksheet. Instead, pose the problem for the students in a pre-lab class session and have them figure out how to solve it- or, even better, try and start them on the path to defining the problem themselves. This will necessarily take more time than doing a canned experiment, which is why you need to dispense with the less important parts of the curriculum.

The following is an example of how this might be done. Suppose the canned experiment is the following:

<u>Investigating Light's Effect on Plants</u>

In this experiment, you will investigate the effect of light on plants.

D(BS)

Materials and Equipment

Eighteen marigold seeds
Potting soil
Six three inch plant pots
Six coffee cans with tops and bottoms removed
Five coffee can lids with holes cut out of their centers, covered with cellophane of the following colors: clear, red, yellow, blue, green
One intact dark plastic coffee can lid
Cafeteria tray
Paper towels
Water

Procedure

1. Fill each plant pot with potting soil (to a point one inch below the rim.)
2. Plant three marigold seeds in each pot, one quarter inch deep and spaced as far as possible apart from each other.
3. Cover each coffee can with one of the prepared lids.
4. Cover the cafeteria tray with a one inch deep layer of paper towels. Place the plant pots on the tray. Water each pot well. Place one coffee can over each plant pot.
5. Put the tray in a well-lit place. Add water to the tray so that the paper towels stay quite wet. Leave the setup alone for three weeks, but make sure that the paper towels stay wet.
6. Remove each coffee can and observe the marigolds underneath. What color are the plants under each coffee can? Measure the height of each plant and record it in your data table.

Questions

1. How did the plants grown under different colors of light differ?
2. Were there any similarities between plants grown in the dark and plants grown under some colors of light?
3. If you were a nurseryman, what kind of light would you want in your greenhouse?

A canned lab can be made more open-ended by following the series of steps described below.

I Introduce the Topic

In this step, you assemble the key concepts needed to understand and provide a rationale for the laboratory experience to follow.

The lab in this example was designed to fit into either a photosynthesis unit or into a plant tropisms unit. The in-class introduction to this lab could begin by having the students tell you what they know about light and plants. The important facts that they raise (for example, plants grow towards the light, plants use light energy to make their food) should be written on the board and discussed as they are raised. Once the knowledge base has been assembled, the students will be primed for the next step in this process. II.

D(BS)

I. Pose the Scientific Problem

This should be done as indirectly as possible, so that the students will have a reasonable opportunity to figure out what the problem is on their own. In this case, instead of telling the students that they will be observing the effects of different colors of light on plants, you could...

Hand each lab group a prism, and have them put it in sunlight and watch the rainbow appear. Ask them to describe the rainbow and tell you what its appearance says about the nature of sunlight. At this point, you can either try to indirectly elicit the key question for the experiment or ask the students directly: do they think that plants need all of the colors of light or only a few? After some opinions are proffered and evaluated by the group.

II. Design, Refine, and Run the Experiment

Break the class into lab groups (four students per group is a good number.) Ask them to think about how they could experimentally find out the answer to the question. Give them some time to brainstorm as lab groups, then collect their suggestions and write the important points up on the board. Discuss the key components for such an experiment: plants, sources of different colors of light, conditions that permit plant growth.

Now, dig out the prepared coffee can lids, plant pots, and so on, and ask the students in each lab group to design an experiment to test the effect of different colors of light on plants using these materials. Let them brainstorm and write down their protocol; then go over each group's protocol with them and evaluate it. Make sure that they have included the full sunlight control and the no sunlight test experiment and that they understand why these things are important; make sure that they have multiple seeds in each pot and understand why this is necessary; ask them what provision their plants will have for water; ask them whether or not it's a good idea for the coffee cans to be removed once a day to water the plants. Also make sure that they have some idea of how they will evaluate thir results: for example, they should have planned to observe the color and size of their plants, measure their heights, and so on. Once a lab group has come up with a reasonable protocol, have them set up the experiment and run it. The precise experimental design may vary from lab group to lab group; as long as their protocols look reasonable, let each lab group follow its own protocol.

IV. Collect and Evaluate the Data

After the experiments have been run, have the students collect their data, evaluate their results, and attempt to answer the initial scientific question based on their results. If their data don't answer the question, have them explain why this is so and suggest modifications to their original protocol that would allow them to attack the question better. In class, discuss their results; also discuss differences (if any) in the results of lab groups that followed different protocols; attempt to account for these differences.

V. Generalize from the Results of Their Experiments

In class, ask the students what questions are raised by their experimental results and list them on the board. Possibilities for this lab include:

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a. Why are plants raised in the dark lighter in color than plants raised in the light?
b. Why are the internode distances in plants raised in the dark or in certain colors of light longer than those of plants grown in full sunlight?
c. Common wisdom says that plants grow towards the light. Why did the plants grown in the dark grow up rather than down or sideways?
d. Can we narrow down the frequencies of light to which plants respond?
e. Are the frequencies required for green color different from those required for short internode distances?

For the most interesting questions, ask the group to suggest experimental approaches that would help to resolve the question. If a really interesting question comes up and someone really wants to solve it, help him design an experiment and run it outside of class, then report his results in class (more extra credit possibilities here...)

In the post-lab class discussion, be sure to have the students answer the questions raised in the original lab questions section if they look worthwhile; also pose open-ended ones of your own. (For example, on a planet circling the star Betelgeuse, sunlight is red. What would marigold plants grown in such sunlight look like?)

While the material presented in both approaches to this laboratory investigation is the same, the students will have participated much more effectively here than they would have by merely following the original canned lab protocol. Many canned question labs can be uncanned in this way; the only real limitations are those posed by safety and time.

B. Problem-Based Learning

In order to convey the feeling of what doing science is all about, it is a good idea to approximate the process involved as closely as is reasonable given the ages of the learners involved. The steps of the scientific research process (see pp. 3-9 for a detailed explanation) are the following:

1. Learn a great deal about your field.
2. Think of a good (interesting, important, and tractable) problem.
3. Decide which experiments/ observations/ calculations would contribute to a solution of the problem.
4. Perform the experiments/ observations/ calculations.
5. Decide whether the results really do contribute to a better understanding of the problem. If they don't, either go back to step 2 and refine your statement of the problem so it's more tractable or go back to step 3. If they do, go to step 6.
6. Communicate your results: talk, publish.

This process bears a remarkable similarity to the experience learners have in a problem-based learning situation. In such a situation, the emphasis is on ill-structured "real" problems initially supplied by the teacher. The teacher acts as metacognitive coach, supplying information and suggestions when asked and the students proceed through a series of group tasks to define the problem and find solutions to it. The group tasks for the students in problem-based learning are the following:

D(BS)

1. Determine if a problem exists.
2. Create an exact statement of the problem.
3. Generate possible solutions.
4. Evaluate the possible solutions, emphasizing differences between facts and inferences, positive and negative effects of possible solutions. Tools for such evaluation could include cost-benefit analysis and ripple-effect diagrams if appropriate (some of these things may not be useful in a particular scientific context).

An example of the use of an approach similar to problem-based learning in the teaching of science was described in a recent news article in *Science* [Can Science Education be Saved? *Science* 250: 1327-1330(1991).] A quote from the article describes it best:
"Yet another example involves trade-oriented high school juniors in Iowa--a class one teacher referred to as the future cosmetologists of America--who focused on the ozone hole as a way to learn about science. To their teacher's amazement, the students were soon clamoring for information: What's an atom? What's a molecule? What does pH mean? The class became the community ozone experts, and college-bound students began to complain that their class was too dull..."

In this instance, a relatively ill-defined concept was presented to a class of less-than-exceptional students and they came up with questions that helped define the problem and its solutions better and got excited about the science involved in the process. The problem-based learning process could be amended for the purposes of science teaching by adding more components of the scientific process. Three changes come to mind:

1. Opportunities for the learners to test their solutions experimentally or through fieldwork are important. They can then generate some of the data required for a solution to their problem themselves, rather than depending entirely on the work of others (teacher-supplied information, information from databases, and so on.)

2 Opportunities for students to manage their own data: they should learn proper data-handling skills including the keeping of a good notebook (suggestions about notebook format are included in Section D of this appendix), photographic techniques to record data when appropriate, and the saving and storage of raw data (never throw anything away). They should also get to analyze their own data, using computer software when appropriate.

3. Opportunities for students to present their solutions (including supporting data.) These could be arranged in either the "talk" or the "publish" format. Groups of students could present their reports orally in a conference format; they could develop a poster and then the different groups could hold a joint poster session; or the class could put together an issue of a "scientific journal" for appropriate distribution.

Incidentally, these three items do not have to be incorporated into a problem-based learning situation to be useful. They are equally appropriate in more traditional learning situations, where "canned" experiments are used to illustrate a scientific concept. The importance of hands-on work cannot be overstressed.

D(BS)

C. Incorporating Experiments and Experimental Design Into a Scientific Problem-Based Learning Experience: A General Outline

The incorporation of experimental design into the overall framework of a scientific problem-based learning experience (SPBLE) should be simple and natural: after all, it 's just an extension of the let-the-problem-come-first, let the students handle the inquiry while the teacher acts as metacognitive coach style of problem-based learning. For teachers designing a SPBLE, though, the precise way in which this can be done can be somewhat elusive. This paper will attempt to give a general outline for how this can be done for any appropriately-designed SPBLE.

Several factors will affect the ease with which real (not canned) experiments can be naturally incorporated into a given SPBLE. The problem needs to have components which are amenable to classroom modelling (preferably experimental modelling, although computer modelling would also be all right as long as the students had some intellectual control over the structure and/or use of the computer model) and/or student fieldwork. Thus, high-tech problems dealing with the behavior of complicated, expensive machines in outer space or medical problems for which meaningful experimentation would require an M.D., a lawyer, and a tall stack of informed consent forms are probably best avoided. In practice, though, if the area of science to be illustrated by the problem has canned student lab experiences available, it will probably be easily incorporated into a SPBLE. It i s probably easier to come up with an appropriate problem if you have a well-defined chunk of science that you' d like the students to explore as well as a set of experiments that you 'd like the students to do already in the back of your mind. While they may surprise you and end up doing only a few of your planned experiments and more of their own, for the sake of good problem design, have a few key experiments in mind.

Introducing the problem to the students need not be any different for an SPBLE than for a standard PBLE. The students will be given the initial scenario, asked what they know and what they need to know, and sent out to do the initial legwork for the problem. After this initial phase, though, some of what they need to know should be readily found experimentally. For example, in a problem dealing with an acid spill on a highway, some of what they need to know might include:

- How concentrated is the acid?
- What will the acid do to the highway?
- What will the acid do to cars driving through it?
- What will the acid do to the living things in the pond next to the highway?
- If we have to clean it up, how do we do it?
- How do you neutralize an acid safely?
- How much neutralizing stuff would we need to do the job?

Many of these questions are amenable to experimental modelling. Although samples of the highway spill may be unavailable (more likely if the imaginary acid is highly concentrated), the teacher should have a wide variety of appropriate materials in the classroom for modelling of relevant aspects of acid-base chemistry. These would include pH paper (one way of determining the strength of an acid); a collection of safe (i.e., kitchen-type) acids, bases, and neutral substances; measuring devices and containers; seeds, water plants, and other ethically appropriate experimental organisms; chunks of concrete (to simulate the

highway); metal, plastic, and other objects (to simulate objects that might come in contact with the spill); and so on.

Once the students have made their list of key questions relating to the problem (such as the list above), the teacher could help them use the four-question strategy described in Students and Research to generate the kinds of experiments that could be done to aid in resolving the questions given the materials available. After a reasonable list has been generated, the teacher could then ask the very important question : Which of these experiments would help us to answer the problem questions that we have listed? For the example described above, the following types of experiments will probably be chosen from the universe of possible experiments generated by use of the four question strategy:

- Use pH paper to determine the concentration of the spilled acid: this can be modelled by having using pH paper to test the pH of a wide variety of substances.
- Try adding base to the acid to attempt to neutralize it : this can be modelled by adding base to their favorite acid and looking for pH (and other) changes (if done incrementally rather than all at once, the students can produce titration curves, not usually encountered until high school)
- Try adding water to the acid to dilute it and increase its pH; easily modelled by adding progressively larger amounts of water to their favorite acid and checking the pH as they go.
- Try soaking different materials in acid to model the effects of acid on the highway and the cars.
- Try sprouting seeds in increasingly acidic solutions or growing water plants in solutions of different acidity to model the effects of acid on living organisms.

The students should be asked to determine the order in which the experiments should be performed. In this situation, the pH paper test needs to come first, because the students need to know which available substance is their strongest acid (and they should be able to come up with the rationale that their strongest acid would probably be the best to model a concentrated acid spill.)

Once the initial priority list has been established, the first experiment should be designed in class with the teacher acting as metacognitive coach and ensuring that the students design a good, workable experiment with appropriate variables, constants, controls, and repeated trials. If the students have never formally encountered experimental design before, the first experiment is an appropriate place to introduce it: the experiment that they will eventually design and perform is, after all, directly relevant to the problem. During the in-class design phase, the students should also generate a protocol that lists every step in the experiment, describes the data to be collected and observations to be made, and sets up data tables for data collection. This protocol should be xeroxed and made available for every student before actual data collection starts. Noncoincidentally, this protocol will look a lot like the instructions for a standard canned experiment: it' s merely a recipe to be followed by the investigators.

Once every student has read the protocol and it is clear to everyone, the actual experiment can be performed. There are many possible ways to group students, depending on the design of the experiment. Individual lab groups of three or four students could each perform the experiment; each student could collect data for a few points and then the class data could be analyzed as a whole; and so on. All data collected by an individual student should be recorded in ink by the student in her lab notebook along with any observations that she makes; all data analysis should also be recorded in her notebook.

D(BS)

Once the data have been collected, they should be analyzed and discussed in class. The teacher needs to elicit discussion on a number of major points, some of which relate to experimental design and some of which relate to the relevance of the results of the experiment to the problem. Suggested questions include:

- Did the experiment work?
- Was the experiment adequate to model the problem situation? How would you change it to make it a better model for the problem situation?
- Did anything unexpected happen when you did the experiment?
- If you were going to do this experiment again, would you change the protocol? Why or why not?
- What do your results imply for our solution to the problem?
- Based on this experiment, are there new questions that we need answered in order to come up with a good solution for the problem?
- Based on the results of this experiment, are there new experiments that we need to design and perform in order to come up with a good solution for our problem?
- Based on this experiment, do we need to change the experimental priority list?

Once the first experiment has been performed and discussed, the other experiments could be divided up as appropriate: if there are time constraints, it might be useful to have different lab groups design and perform different experiments and report their results to the class. For each experiment, though, careful teacher attention must be paid to the design phase and generation of a good experimental protocol before any reagents are actually used; similarly, careful attention to analysis of the data and teacher-facilitated in-class discussion of their implications is a must. This process of student-directed experimentation and data analysis provides many opportunities for the teacher to work on metacognition and the development of good scientific habits of mind; it will also deepen the students' understanding of the science involved in the problem and give them direct ownership of some of the science needed for the problem' s solution.

Experiments can thus be an integral part of an SPBLE. Indeed, they are necessary in order for the students to experience the full potential of an SPBLE to model the real scientific process.

D. New Science

One of the salient features of science is that it has frontiers which are constantly being pushed back by new research. Children rarely get a sense of this because, as novices, everything is equally new to them, whether it was discovered last week or several hundred years ago. It is important to help them get a feeling for this, though, because it is one of the most exciting things about science: even an experienced professional gets to learn something new about the universe every day, either through his own research or through learning about the results obtained by other scientists.

Information about new science is easy to come by and should be made a part of any science class. Students and teachers can bring in articles from the popular press about new science and present them in a "Current Events in Science " format. Sources for teachers include:

- The Tuesday Science section of The New York Times.

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•Many magazines, including Natural History, National Wildlife, Smithsonian, Science News, American Scientist, Scientific American, Discover, Science and Nature. Although the last two are technical journals, the first half of each is devoted to science news written at a level that any educated adult should be able to understand. Scientific controversies, such as the current fuss over whether low level electromagnetic fields can cause cancer, are usually given a more balanced and complete airing here than in any other place.

•PBS television programs on science are quite useful. The series NOVA is especially good; the people who make this series pick important topics and talk to the right people about them. Its coverage of science is of comparable quality to the coverage of the news by The MacNeil/Lehrer News Hour. The News Hour also does a good job of conveying science. National Public Radio also does a good job of presenting science in its news programs All Things Considered and Morning Edition.

Sources for students include:

•The magazines Your Big Backyard and Ranger Rick: although the science may not be the absolute latest, it may interest the students enough that they'll want to talk about it; this should be strongly encouraged.

•The PBS program 3-2-1 Contact is excellent; National Geographic specials can be quite good; in addition, any number of nature programs could be used.

•Older (or exceptionally bright) students will probably get a lot out of the PBS programs listed for teachers; they will probably be able to handle the publications National Wildlife, Discover, and possibly Science News as well.

E. Real Live Scientists

One way to enliven science teaching is to bring scientists into the classroom along with their science. This is important because contact with scientists is not a part of everyday life for most children, and thus science as an occupation is more mysterious to students than medicine, firefighting, or business. Their understanding of what a scientist does all day and why someone would actually want to do science for a living is thus limited.

There are a number of ways to enhance children's appreciation of the human side of science. This can be done, for example, by bringing in biographies of scientists or popular works (such as the naturalist books by Gerald Durrell) that illustrate the scientific process with personal anecdotes. Even better, it can be done by bringing real live scientists into the classroom, bringing them along on field trips, or visiting their labs.

Finding scientists is pretty easy. Some sources include:

•Parents of the students in your school

•Government agencies: the U.S. Geological Survey, the Environmental Protection Agency, the National Bureau of Standards, and many other Federal agencies have public education as a part of their mission, and their scientists are encouraged to participate in the enlightenment of the nonscientific community. In addition, there are state agencies, such as the Department of Fish and Game and the state geological surveys that also encourage their people to get involved. All of these agencies can be found simply by checking the government pages in the telephone book.

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•Local universities: talk to their public affairs office about campus museums, tours, and the possibility of getting a scientist to visit your classroom.

•Local industry: many corporations encourage their scientists to go out into the community and educate people about the work that they do. Check with the public relations department.

When recruiting a scientist to come into the classroom or go on a field trip, try to do the following things:

1. Have a concrete idea of what you would like to have them do. Asking a geologist to come tell a class about geology is not as helpful as telling her that you are studying metamorphic rocks and would like her to tell the class more about them and bring samples. It's fine to ask the scientist for suggestions (i.e., would it be better to take them on a field trip to illustrate this idea or would a lecture be better?), but try to have some idea of the topic in mind.

2. Prepare the students. Ask the scientist if she can recommend any reading or activities for the students (or for you!) on the topic she'll be discussing; prepare the students in advance and they'll get more out of it as will the scientist.

F. Notebooks

Proper notebook-keeping is a scientific skill that can be learned early and may be helpful outside of science as well, as the same care is needed to maintain a checkbook or keep records for tax purposes. Notebooks constitute a permanent record of the scientific process. To avoid losing information, a scientific notebook is best kept in a bound blank book or a spiral notebook (preferably one with pockets for large photographs or other records.) A notebook should contain everything pertinent to the experiments and observations that it records. This information includes:

1. The date that the experiment was performed.
2. The title of the experiment (for example, Frog Dissection I or Repeat Sequencing Gel 27-AARGH!).
3. A description of the experimental setup; lists of reagents used, methods employed
4. The raw data for the experiment (sometimes this is impractical: for example, 14x17 inch sheets of X-ray film do not fit into a spiral notebook. Raw data that do not fit in the notebook should be labeled with the experiment date and notebook page that describes their acquisition and stored elsewhere.)
5. Notes pertinent to the results (for example, if the power went out in the middle of the experiment and there is some reason to think that this could affect the results, this should be noted).
6. Data analysis
7. Interpretation of the results.

In addition to this information, many scientists describe the thinking process that led them to the experiment as well as their thoughts about its implications and what they need to do next. This can be important, for example, in later patent fights: recording a new idea and the date that it occurred to the scientist in a notebook that shows a consistent pattern of such information helps to establish scientific priority for that idea. It is also a good way to clarify one's thinking before plunging into benchwork again.

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Summary

All of these considerations in teaching science to high ability learners can impact positively on the quality of their learning experience. Effective science teaching and learning requires simultaneous attention to several key areas. Teachers need to know what the most important ideas are in science and how they might be explored with high ability students at K-8 levels. Teachers need to know how scientists do science and model that behavior in expectations for their students. Teachers also need guidance in applying important approaches in doing science in the classroom setting such as incorporating laboratory work, problem-based learning, experimental design, new science, using real scientists, and keeping data notebooks. This guide has addressed all of these areas, hopefully in a way that teachers can implement with high ability students.

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The Skeptical Inquirer is a quarterly magazine published by the Committee for the Scientific Investigation of Claims of the Paranormal. It is probably the single best source of information on pseudoscience and of articles describing scientific tests of the claims of astrology, creation science, and the like. The address for subscription information is The Skeptical Inquirer, Box 229, Buffalo, New York, 14215-0229. Rates as of March 1991 are $25.00 per year.

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